RESULTS AND PROSPECTS FROM THE NOVA EXPERIMENT

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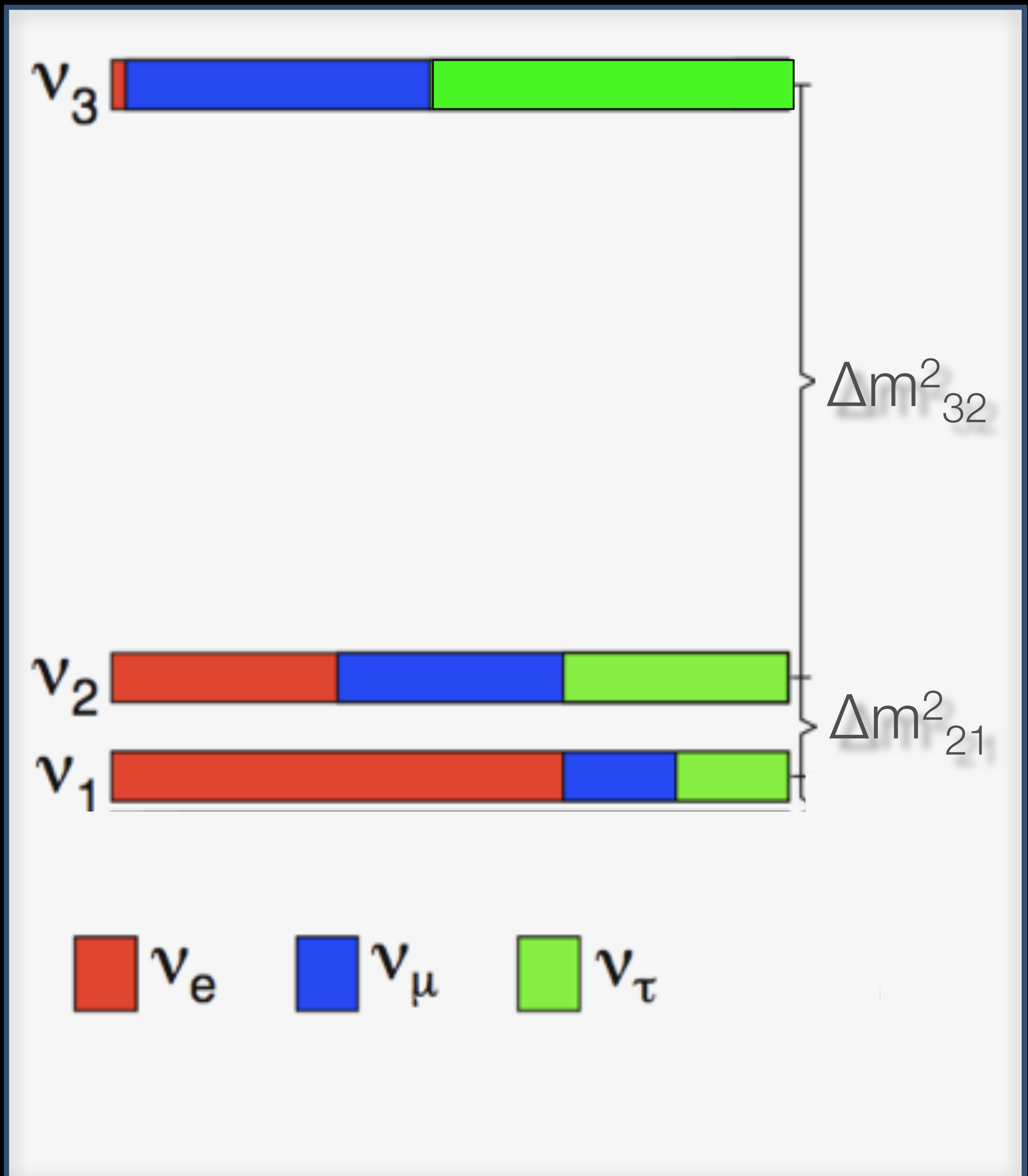
THE NOVA EXPERIMENT IN A NUTSHELL

- Upgrade existing high intensity NuMI **beam of muon neutrinos** at Fermilab from 350 to 700kW.
- Construct a highly active liquid scintillator **14-kton detector** off the main axis of the beam.
  - Low-z detector to better observe electrons.
  - Detector is **14 mrad off-axis**. Location reduces background for the search.
  - Detector on the surface.
- If neutrinos oscillate, **muon neutrinos disappear** as they travel and **electron neutrinos appear** at the Far Detector in Ash River, 810 km away.

2nd generation
← long baseline →

THE GOALS OF THE NOVA EXPERIMENT



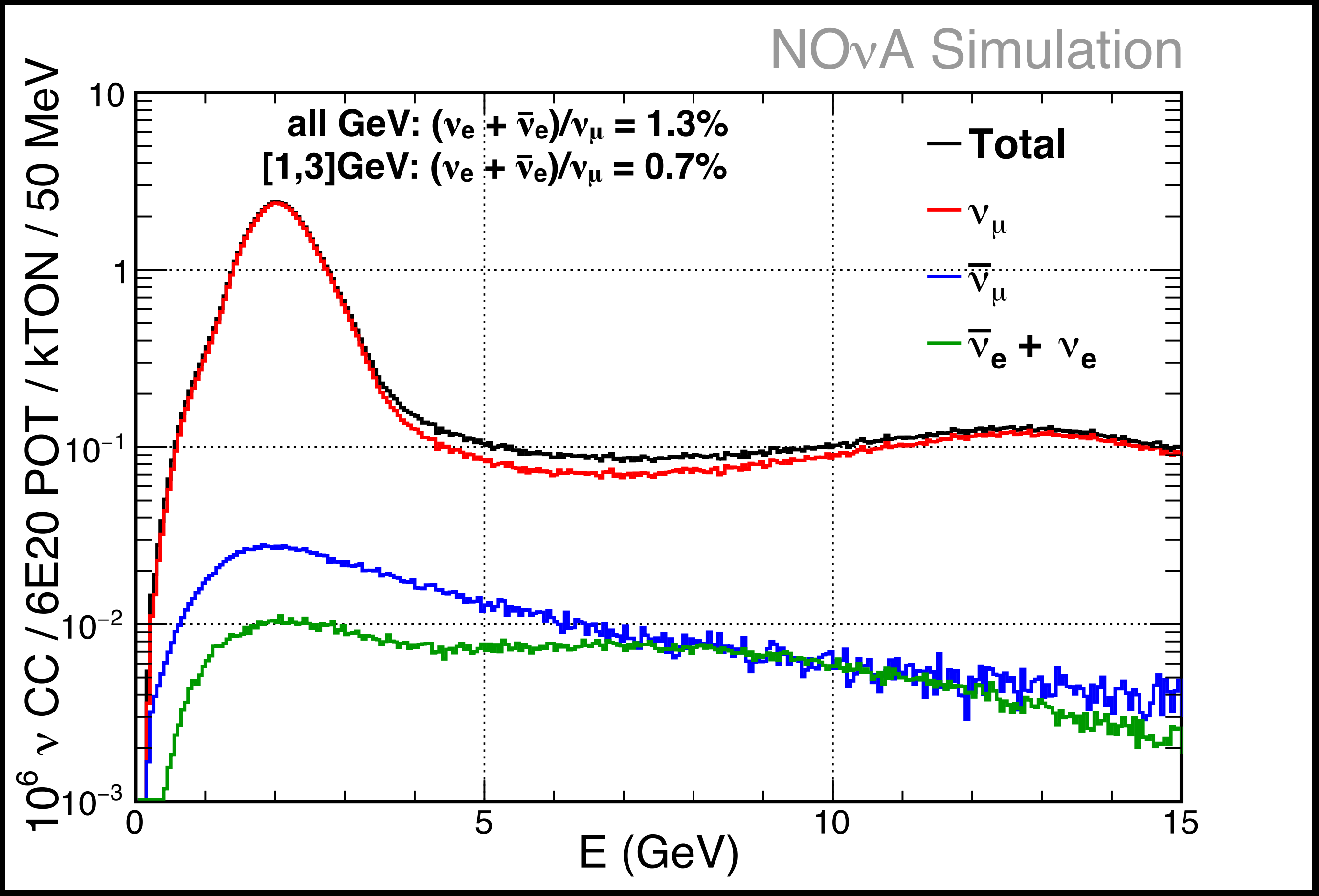
FIRST STEP OBSERVE DISAPPEARANCE AND APPEARANCE FOR NEUTRINOS

- Measure the oscillation probabilities of $\nu_\mu \rightarrow \nu_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ as well as $\nu_\mu \rightarrow \nu_e$,$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$.
  - Precision measurements of Δm^2_{32}, θ_{23}.
  - Determine neutrino mass hierarchy.
  - Study the phase parameter for CP violation δ_{CP}.
  - Resolution of the θ_{23} octant.
- As well as:
  - ν cross sections and interaction physics.
  - Sterile neutrinos.
  - Supernovae and monopoles!

THE NOVA COLLABORATION

Argonne National Laboratory · University of Athens · Banaras Hindu University · California Institute of Technology · Institute of Physics of the Academy of Sciences of the Czech Republic · Charles University, Prague · University of Cincinnati · Czech Technical University · University of Delhi · Fermilab · Indian Institute of Technology, Guwahati · Harvard University · Indian Institute of Technology · University of Hyderabad · Indiana University · Iowa State University · University of Jammu · Lebedev Physical Institute · Michigan State University · University of Minnesota, Crookston · University of Minnesota, Duluth · University of Minnesota, Twin Cities · Institute for Nuclear Research, Moscow · Panjab University · University of South Carolina · Southern Methodist University · Stanford University · University of Sussex · University of Tennessee · University of Texas at Austin · Tufts University · University of Virginia · Wichita State University · College of William and Mary

THE OFF-AXIS NUMI BEAM

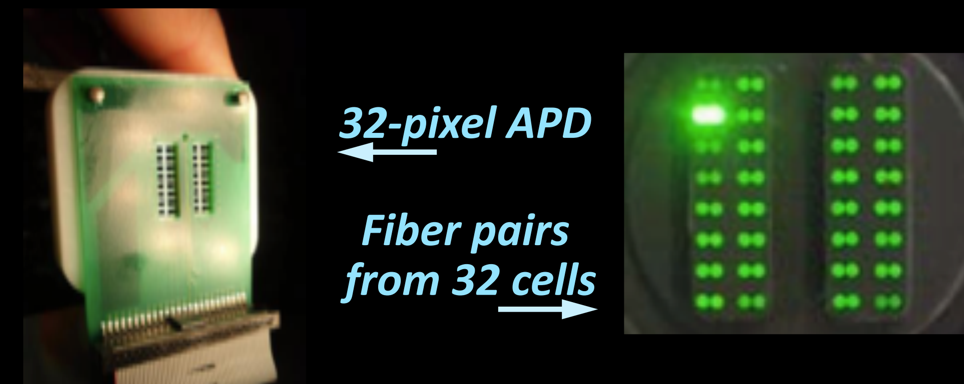


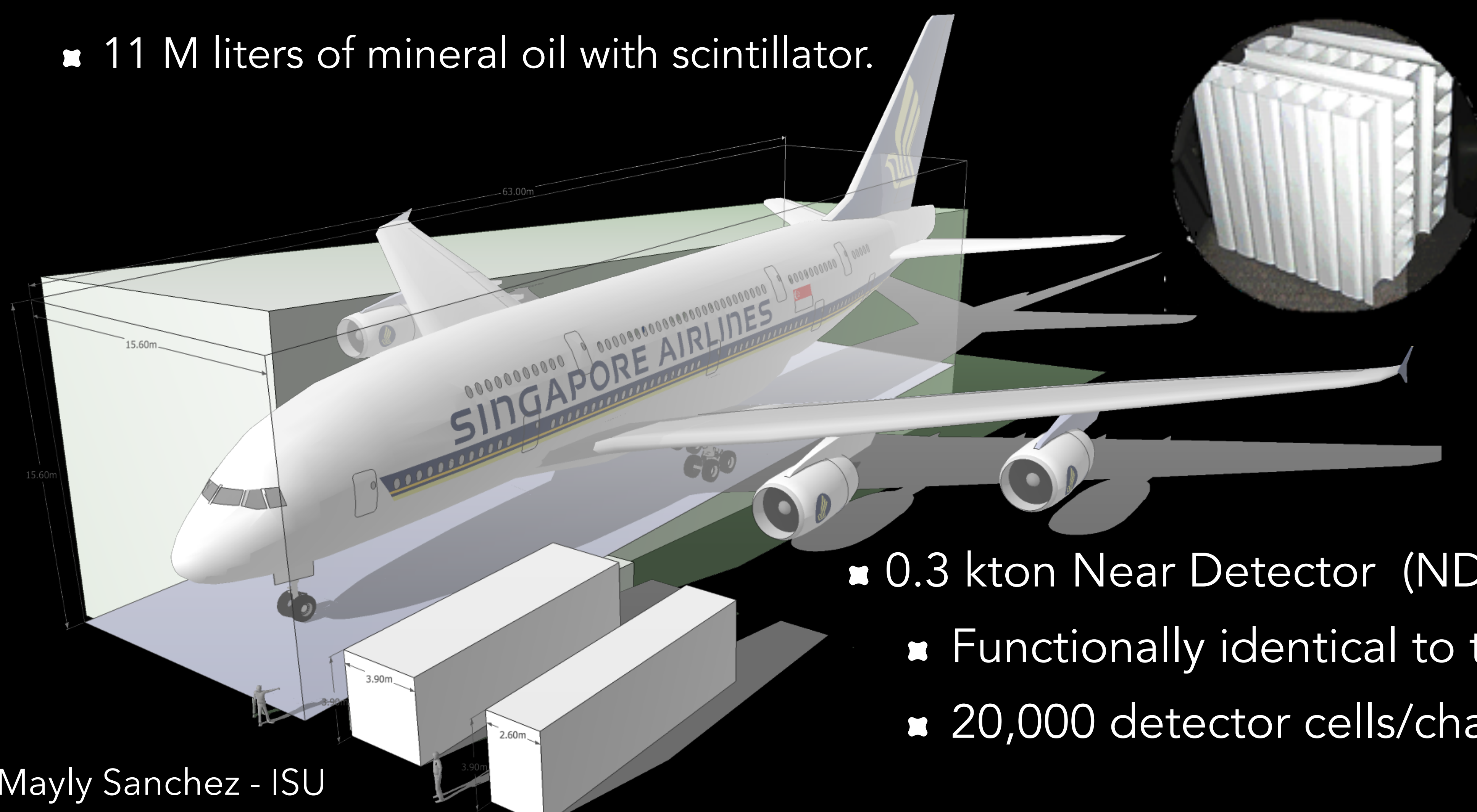
- NOνA detectors are located 14 mrad off the NuMI beam axis.
- With the medium-energy NuMI configuration, it yields a narrow 2-GeV spectrum at the NOνA detectors.
- Small contamination of electron neutrinos in a mostly pure muon neutrino beam.

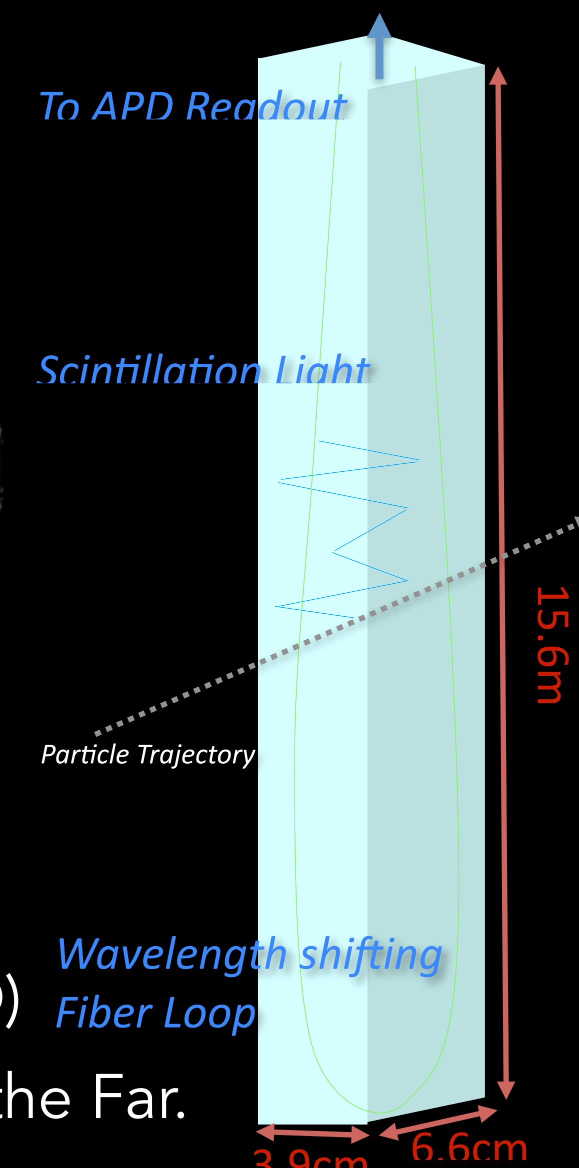
- In FY15 NuMI beam routinely operated at 400 kW for NOvA. Overall uptime: 85%
- Peak intensity of 520 kW achieved.
- A total of 3.45E20 POT delivered is used for these analyses equivalent to 2.74 E20 POT with full 14 kton detector.
- Data taken from February 6, 2014 and May 15, 2015 with detector still under construction.

THE NOVA DETECTORS

- 14 kton Far Detector (FD), low-Z, tracking calorimeter, on the surface.
  - 65% active detector mass.
  - Largest free standing plastic structure in the world: 15.6 meters tall and wide, 60 meters long.
  - Each plane just 0.15 X_0. Great for e^- and π^0.
  - 344,000 detector cells read using wavelength shifting fibers and APDs.
  - 11 M liters of mineral oil with scintillator.

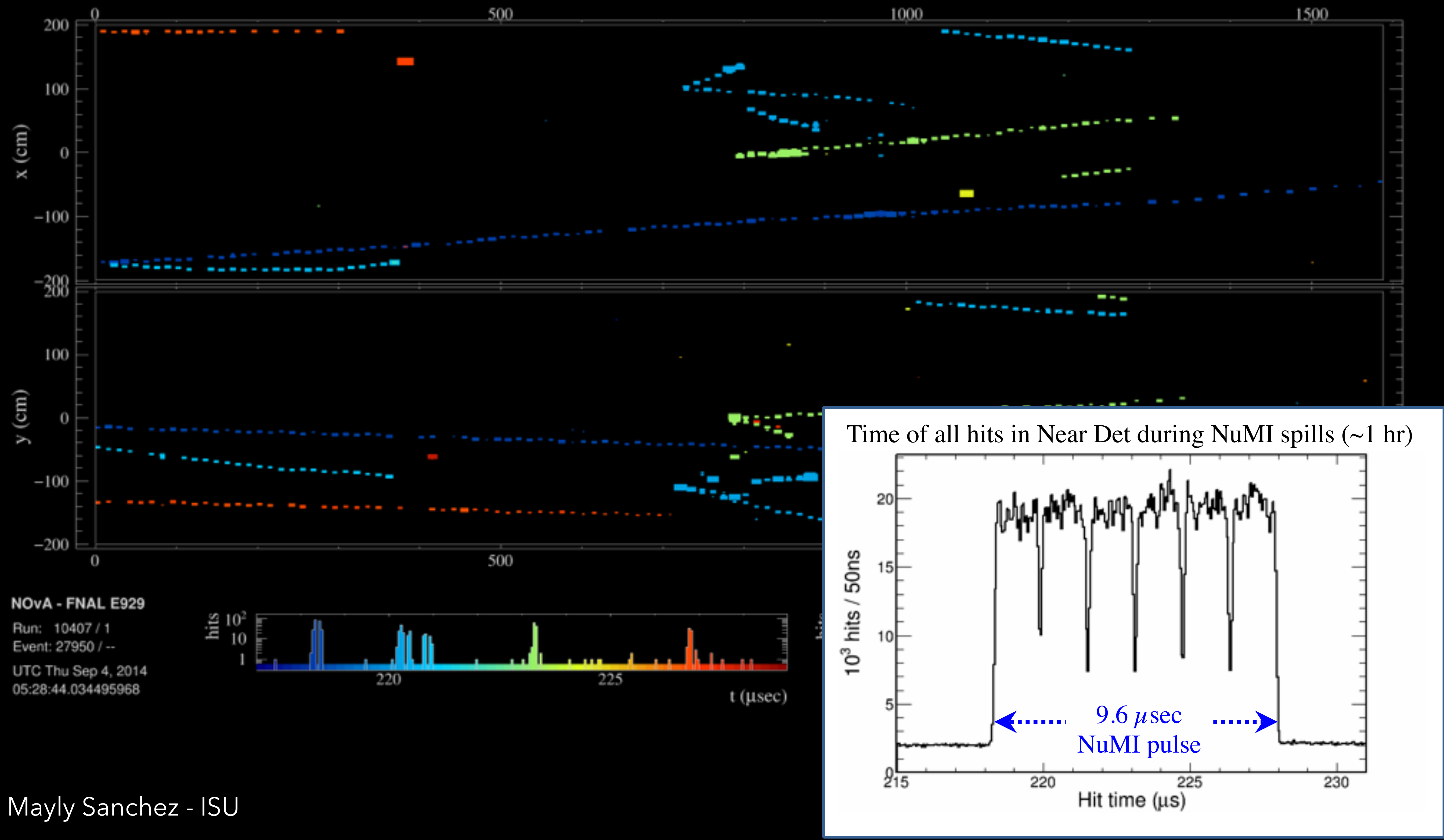






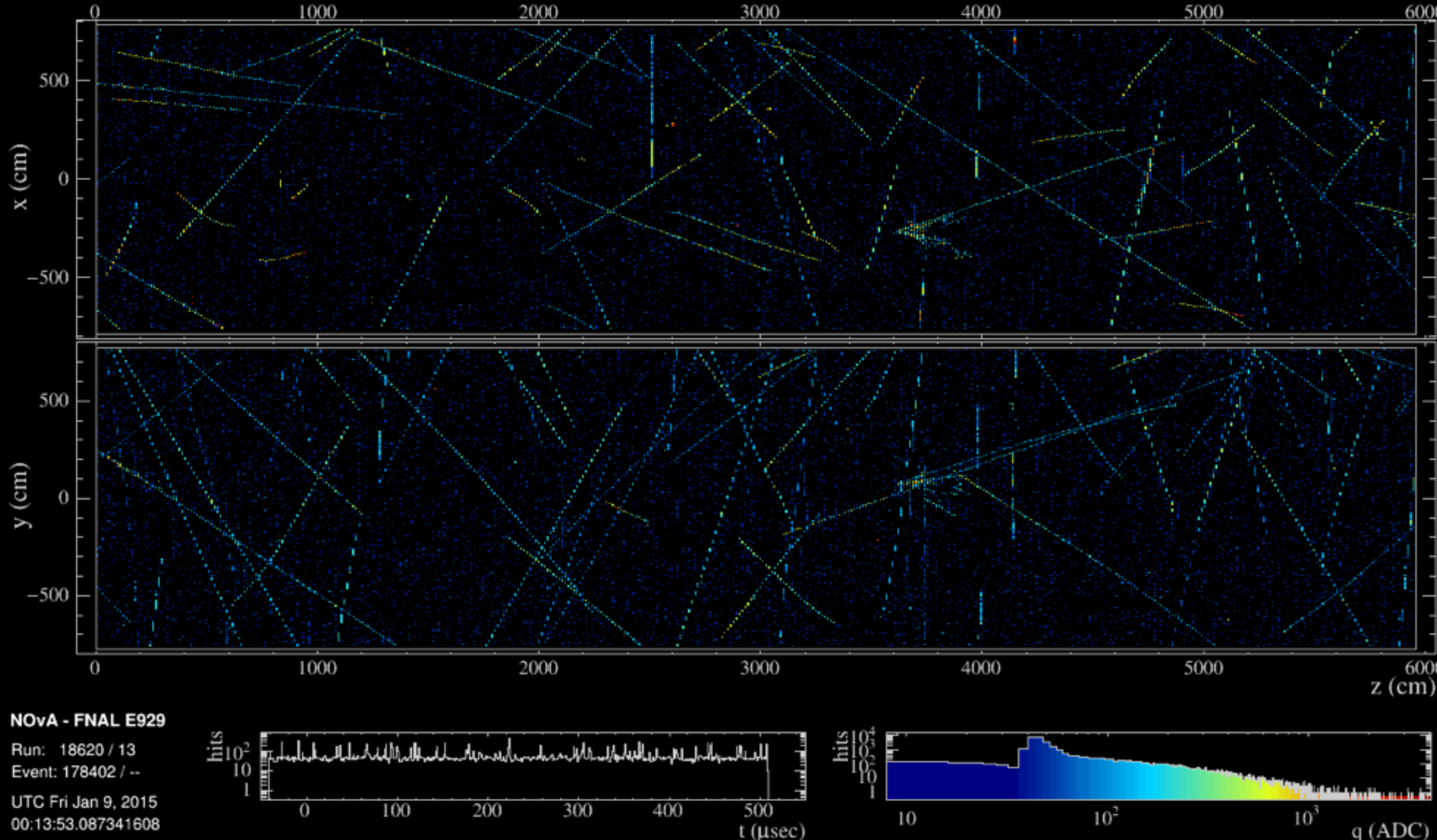
- 0.3 kton Near Detector (ND)
  - Functionally identical to the Far.
  - 20,000 detector cells/channels.

NEUTRINOS IN THE NEAR DETECTOR



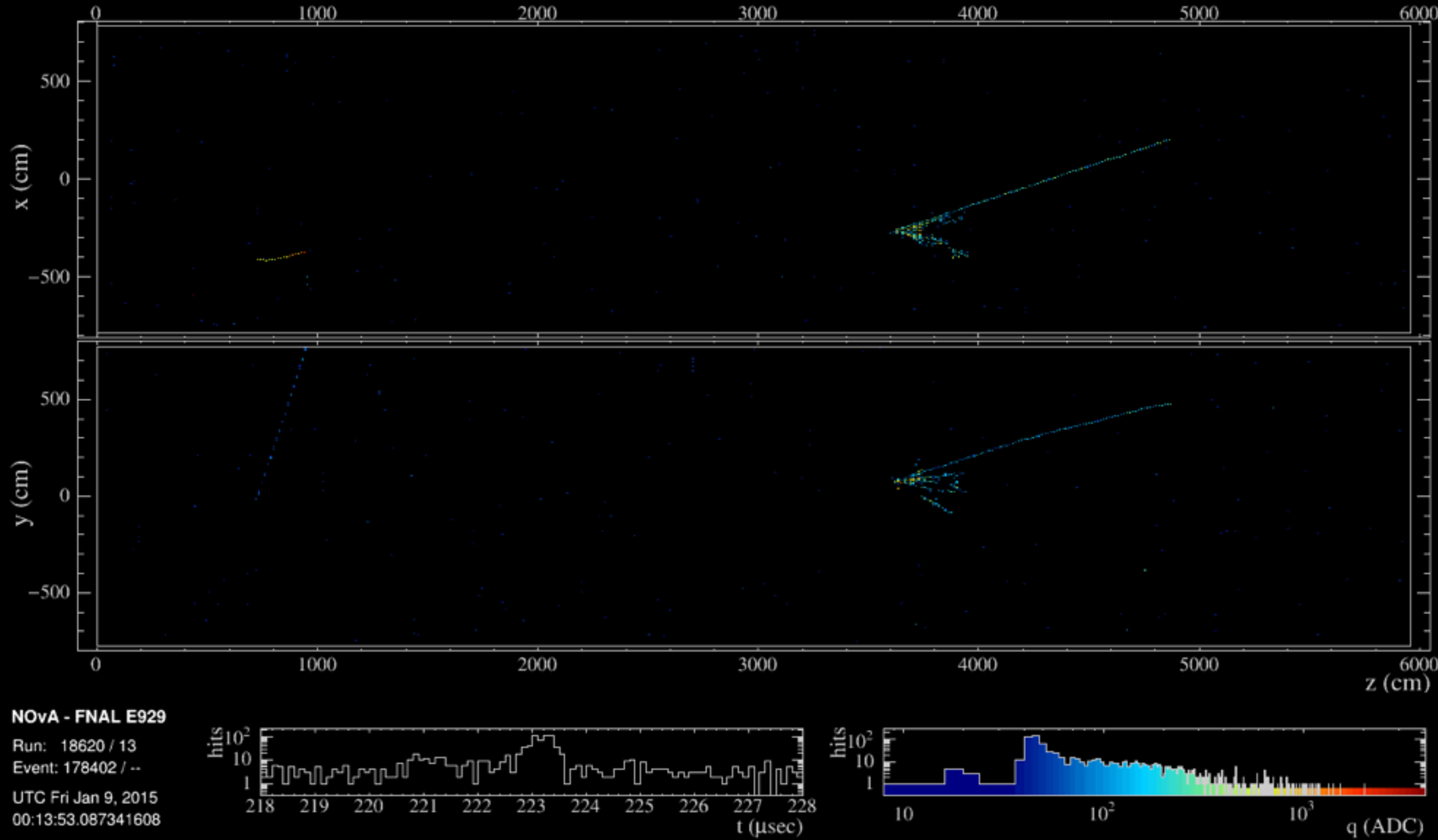
SEARCHING FOR NEUTRINOS IN FD

Beam spill trigger: 500 μsec

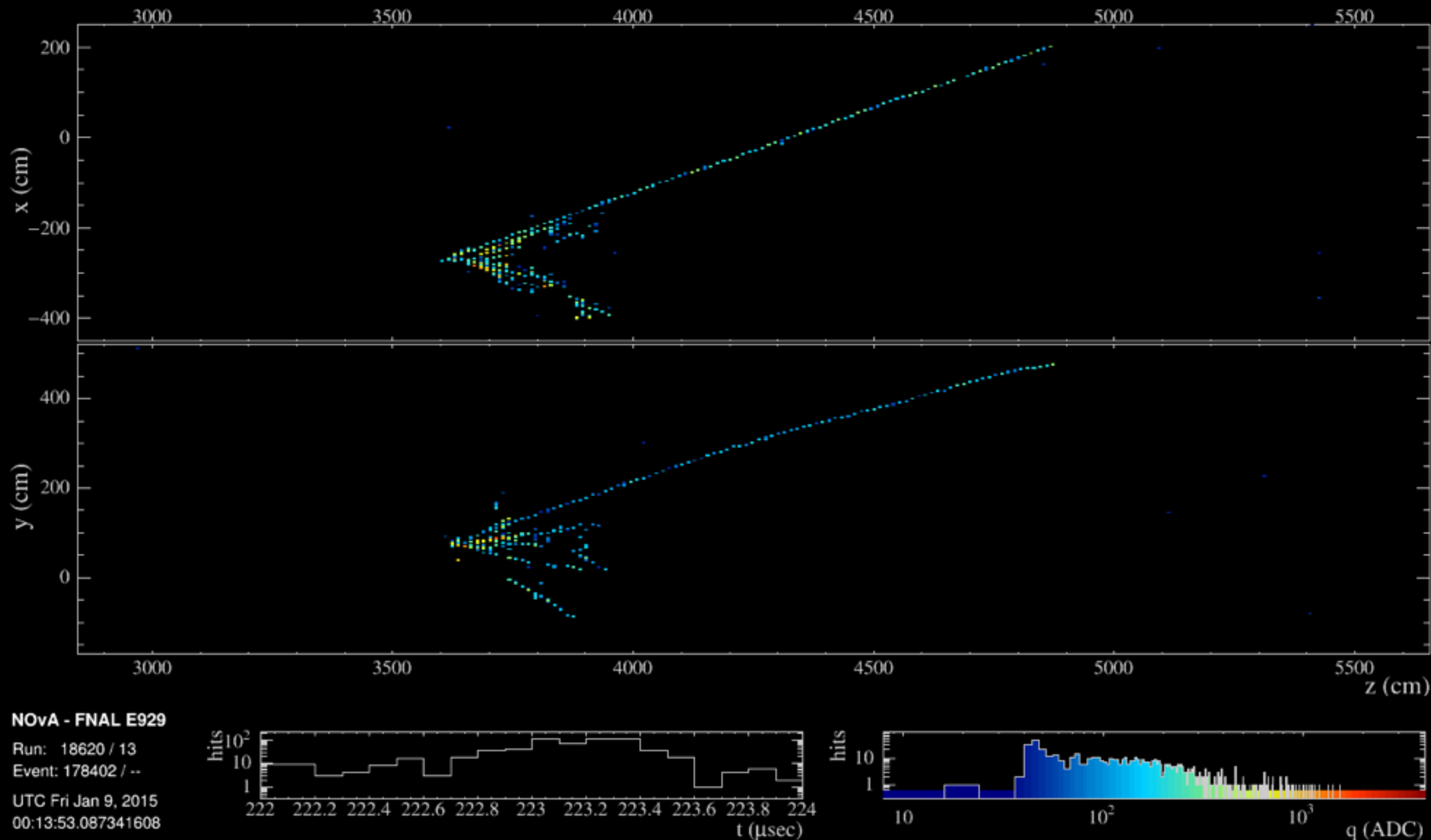


SEARCHING FOR NEUTRINOS IN FD

Beam spill trigger: zoom 10 μsec



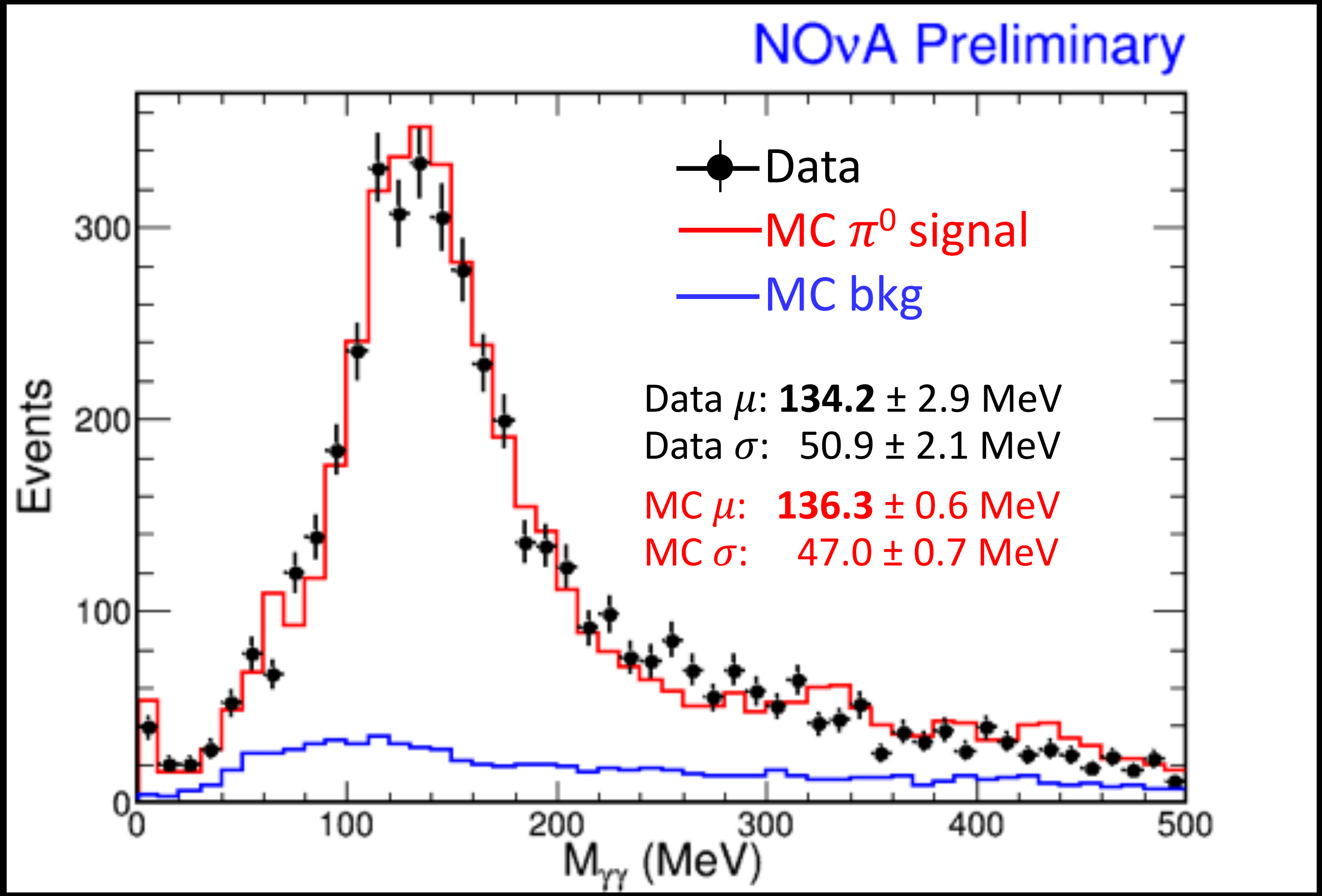
A NEUTRINO CANDIDATE

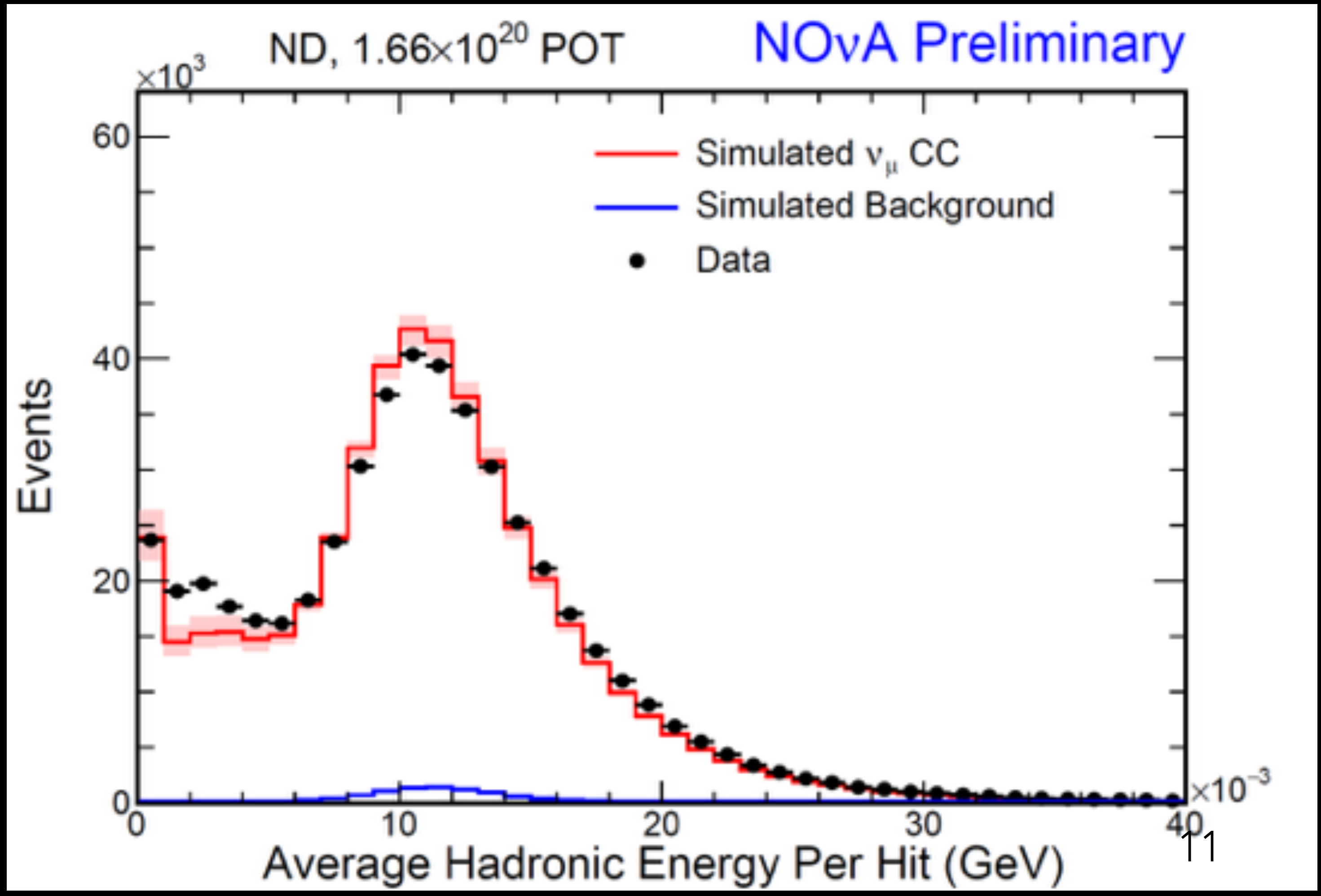


CALIBRATION AND THE ABSOLUTE ENERGY SCALE

- Stopping muons provide a standard candle for setting absolute energy scale.
- Several samples demonstrate successful energy scale calibration:
  - cosmic μ dE/dx [~vertical]
  - beam μ dE/dx [~horizontal]
  - Michel e- spectrum
  - **π^0 mass**
  - **hadronic shower energy/hit**

ALL SAMPLES AGREE WITHIN ±5%

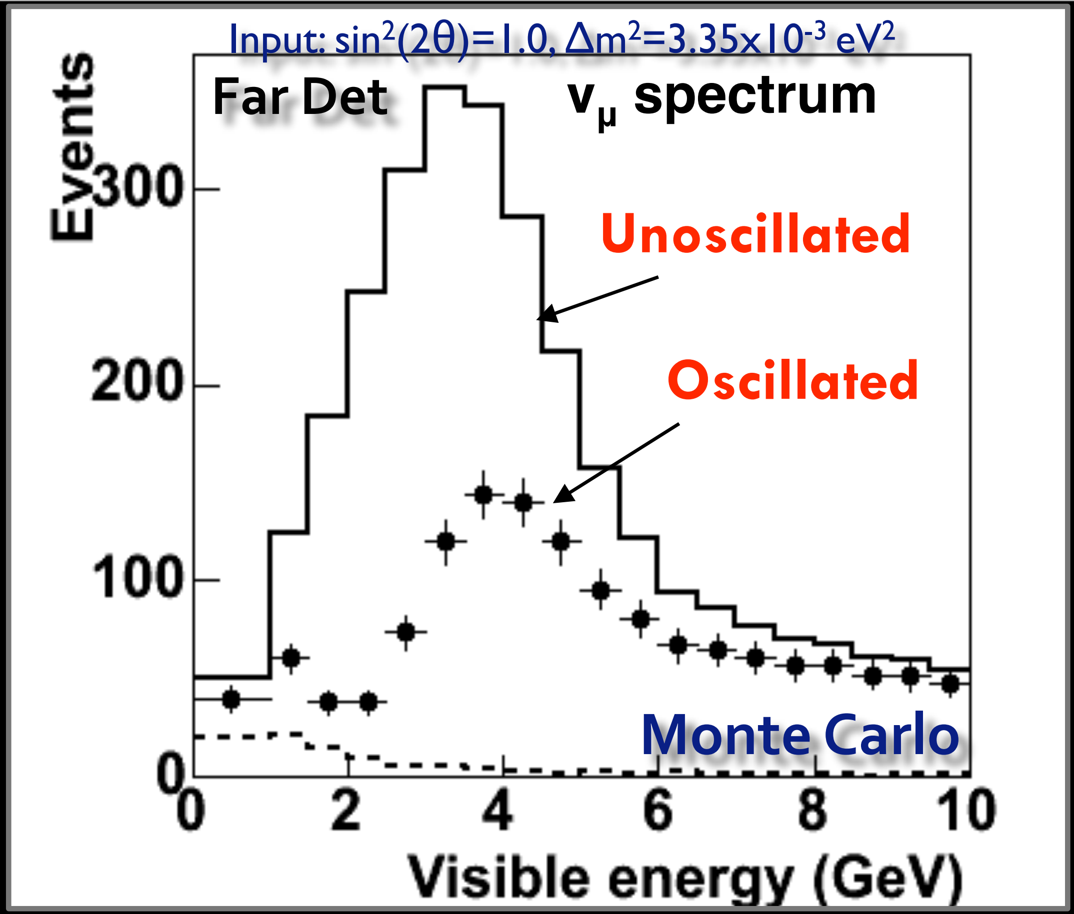


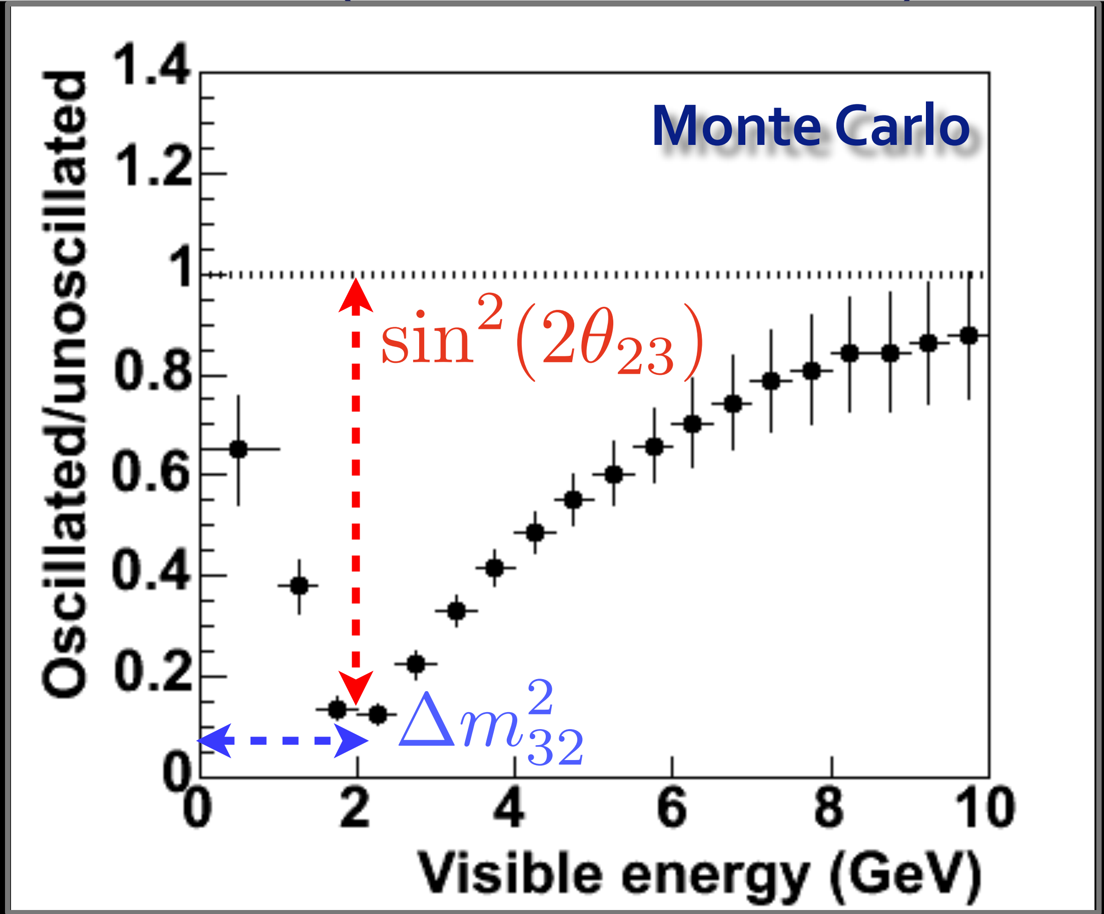


MUON NEUTRINO DISAPPEARANCE

- In long-baseline experiments, we compare a prediction of the muon neutrino spectrum obtained from Near Detector data with a Far Detector measurement. Neutrino oscillations deplete rate and distort the energy spectrum.

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - \sin^2(2\theta_{23}) \sin^2\left(1.267\Delta m^2_{32}\frac{L}{E}\right)$$



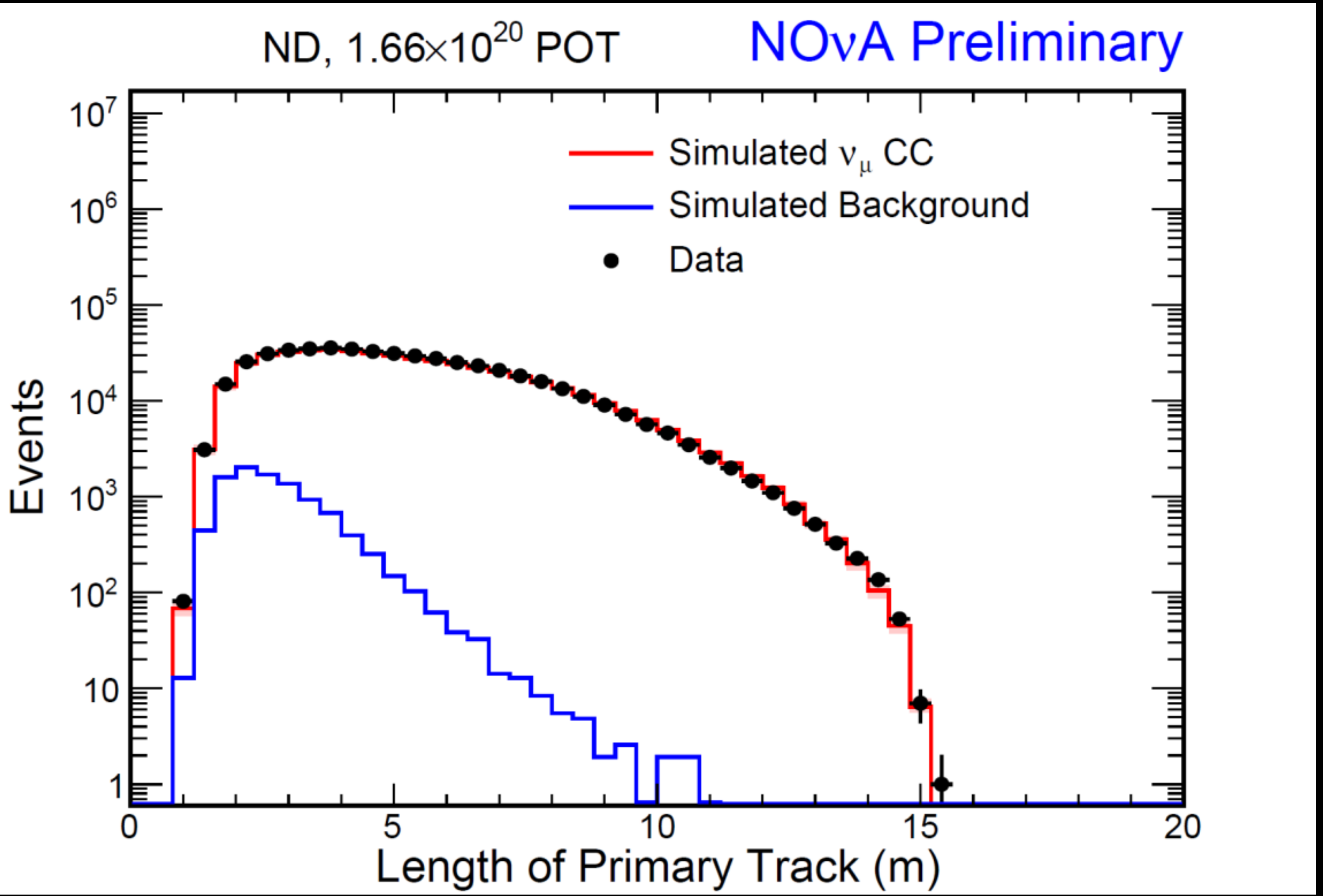


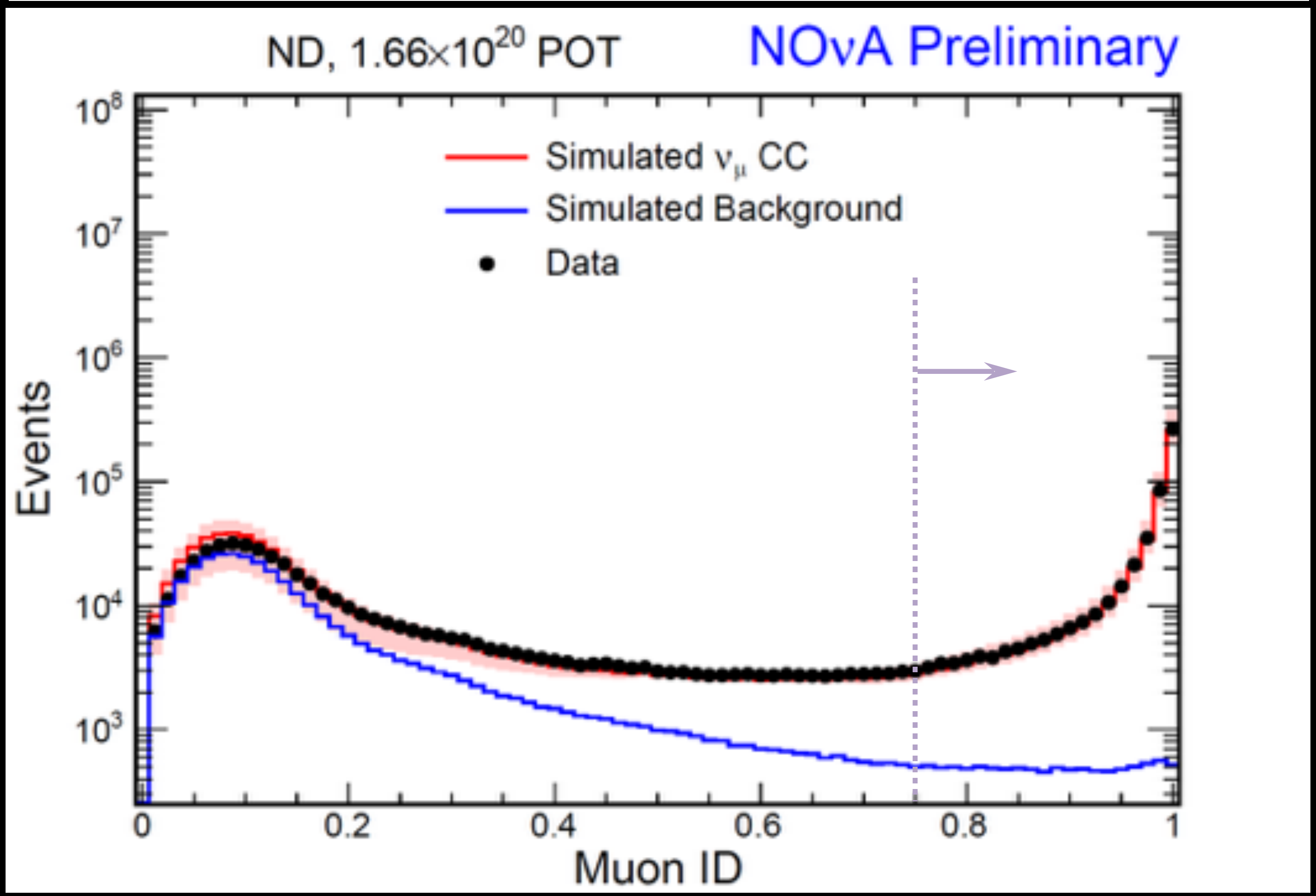
IN AN OFF-AXIS EXPERIMENT NEAR THE OSCILLATION MAXIMUM THE EFFECT IS EVEN MORE DRAMATIC

MUON NEUTRINO SELECTION

- We apply first basic containment cuts requiring no activity close to the wall of the detector.
- Excellent agreement of muon based data vs MC.
- We have developed a particle identification algorithm (k-nearest-neighbors) based on muon characteristics:
  - **track length**
  - dE/dx along the track
  - scattering along track
  - track-only plane fraction

See J. Paley's talk for more ND data vs MC





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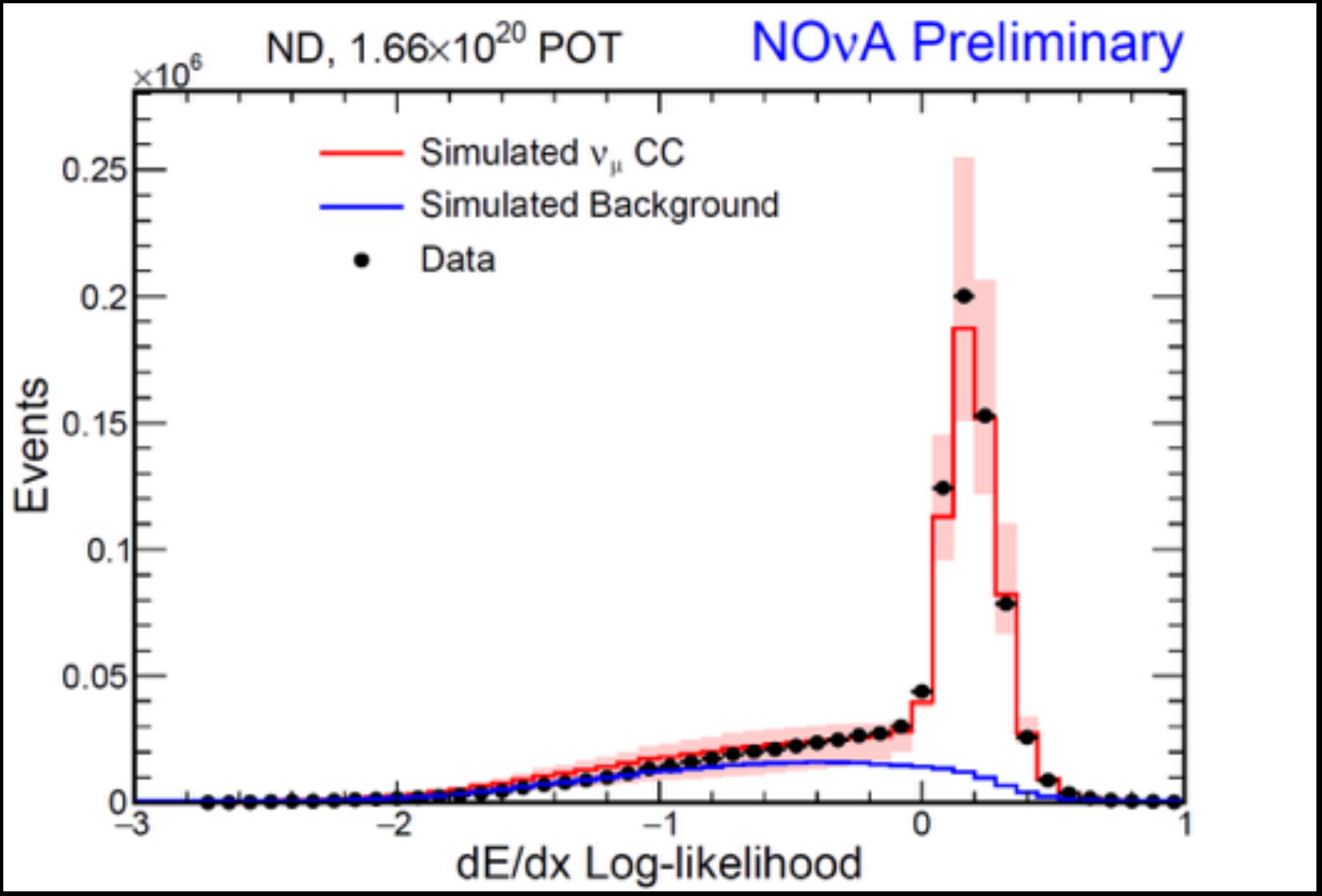
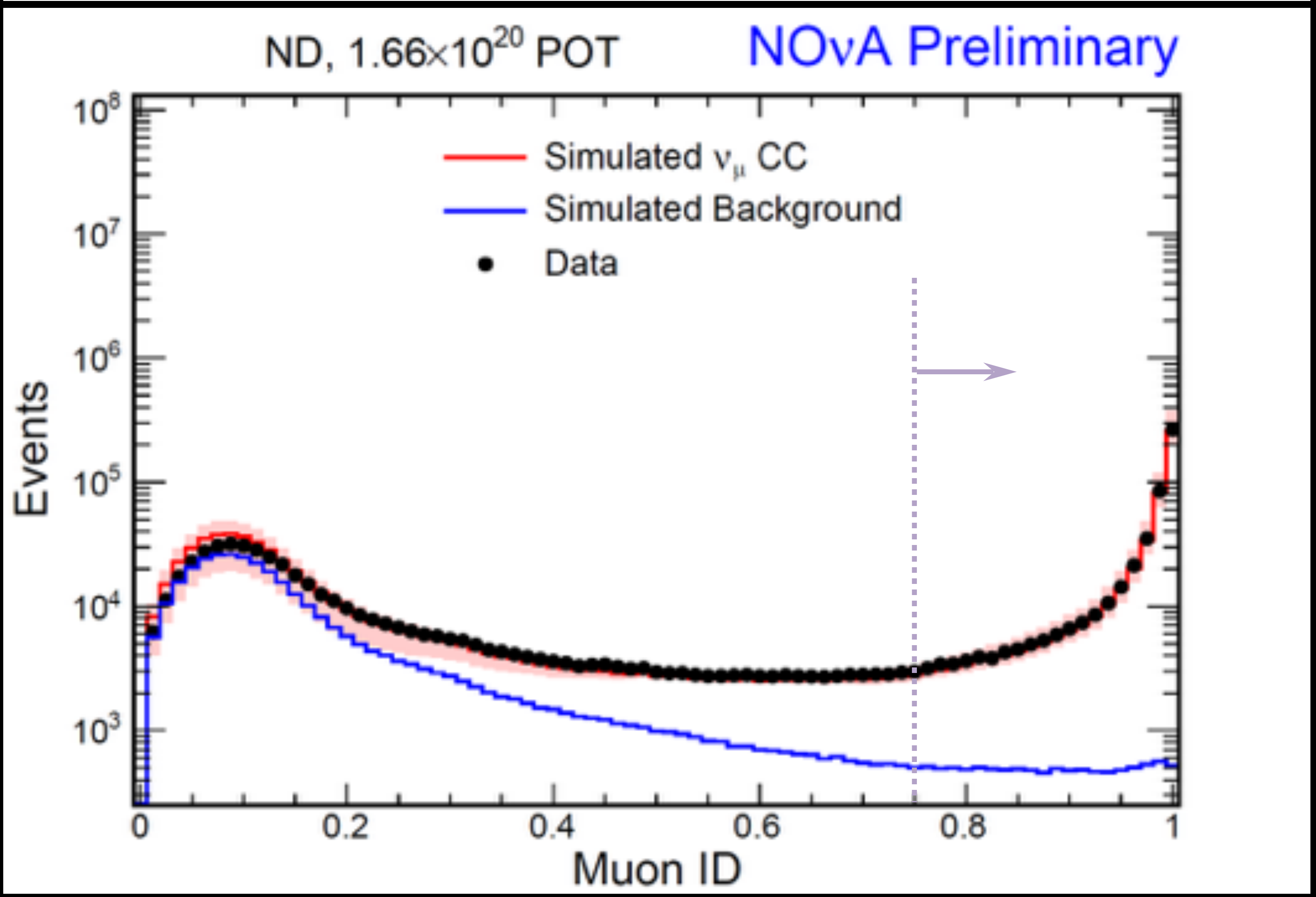
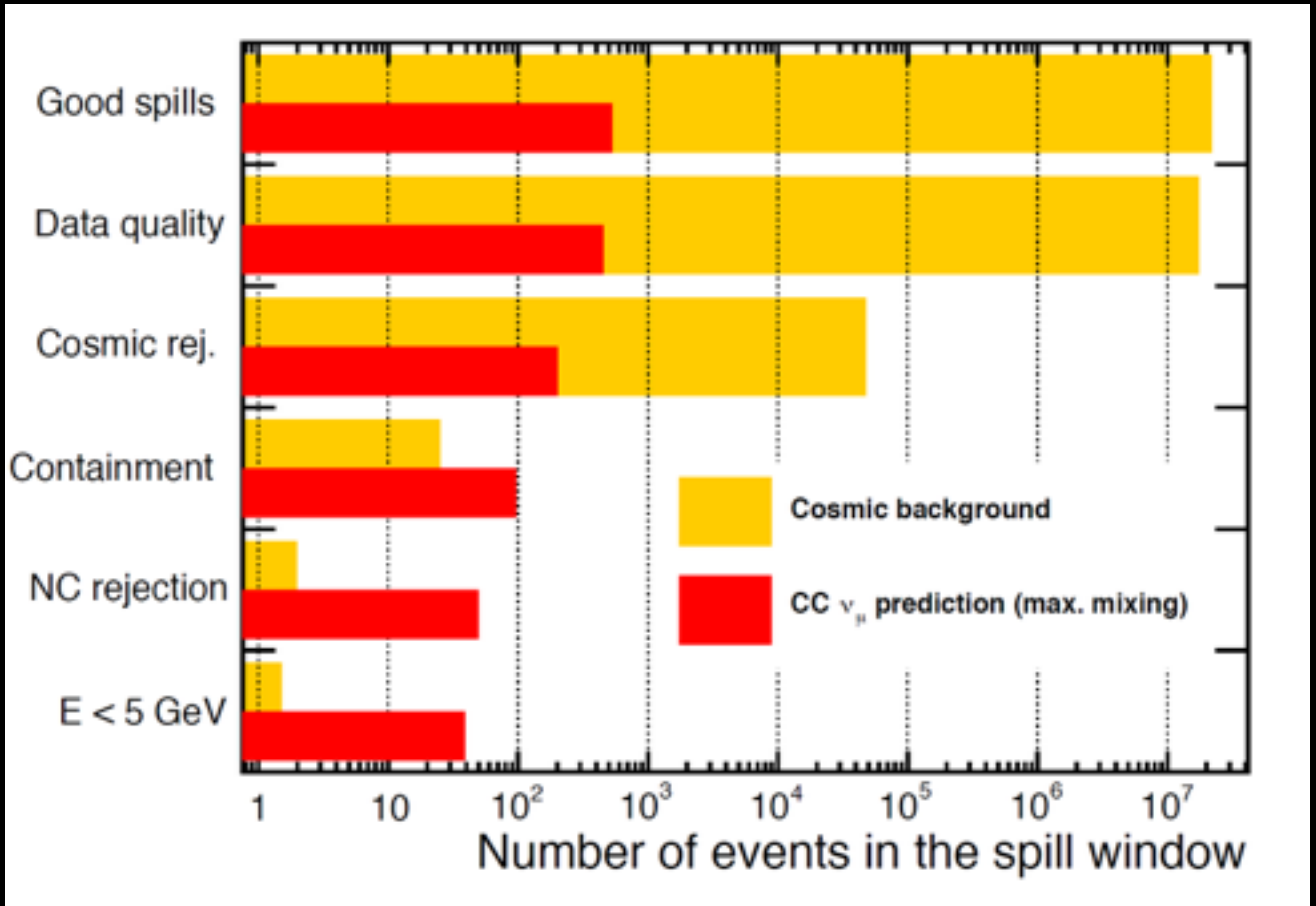
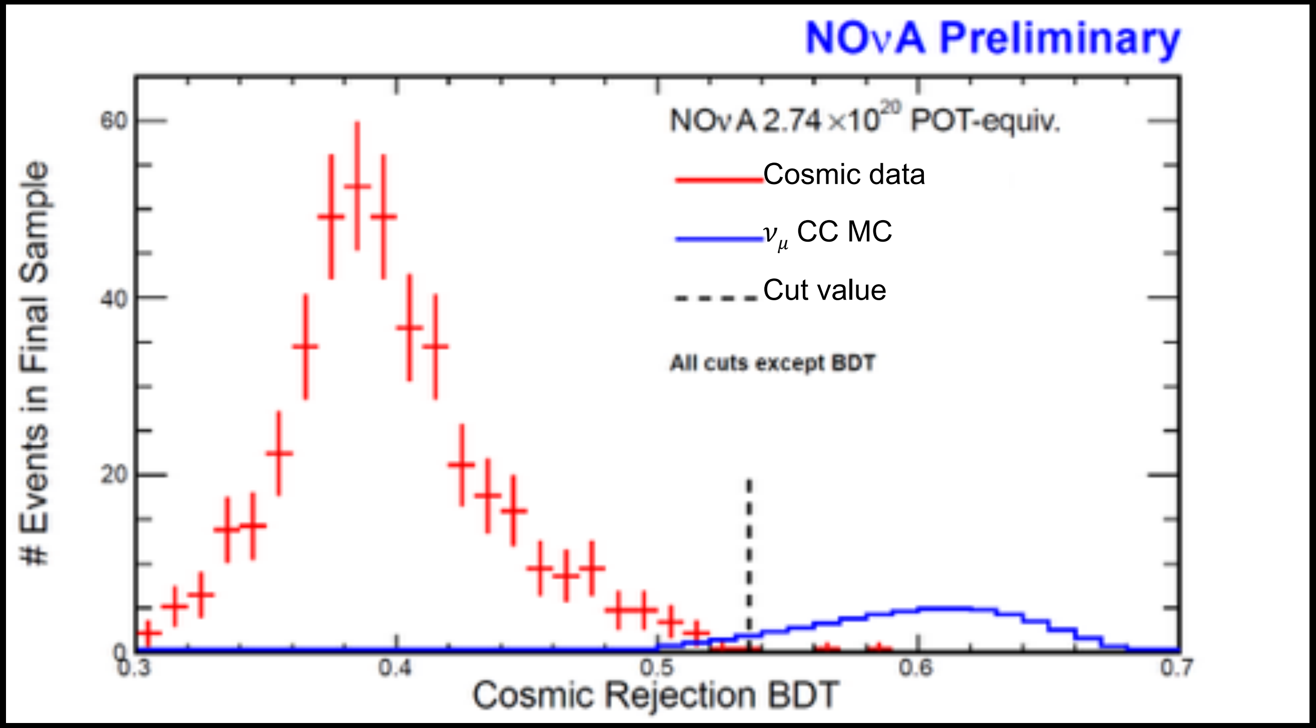




COSMIC REJECTION FOR MUON NEUTRINOS

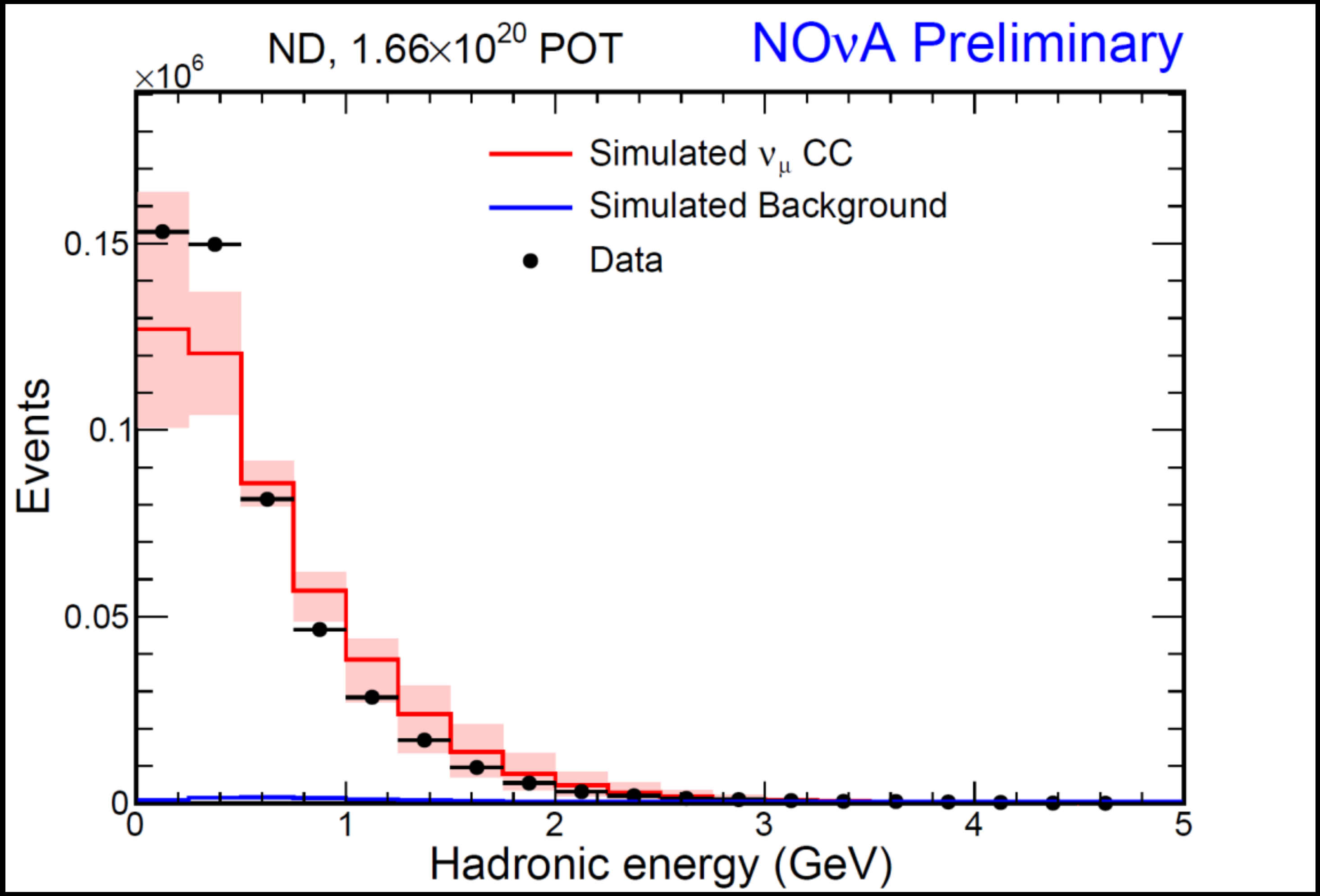
- Final cosmic background rate is measured directly from data taken concurrently with beam spill by using the out-of-time window.
- Selecting a narrow window around the 9.6 µsec spill gives a rejection factor of 10^5.
- For the cosmic rejection of the muon neutrino disappearance analysis, we use a boosted decision tree algorithm based on:
  - Reconstructed track direction, position, and length; and energy and number of hits in event.
- Event topology gives an additional factor of 10^7 rejection.





MUON NEUTRINO ENERGY

- Data vs MC show good agreement for muon neutrino selected events.
    - Muon particle are well described by our MC.
- However, Monte Carlo has 21% more energy in the hadron system than seen in data.
- The hadron energy is thus recalibrated such that the total energy peak of the data matches the MC.
- This results in 6% overall neutrino energy scale uncertainty.



ND DATA IS USED TO PRODUCE A DATA DRIVEN PREDICTION IN THE FD

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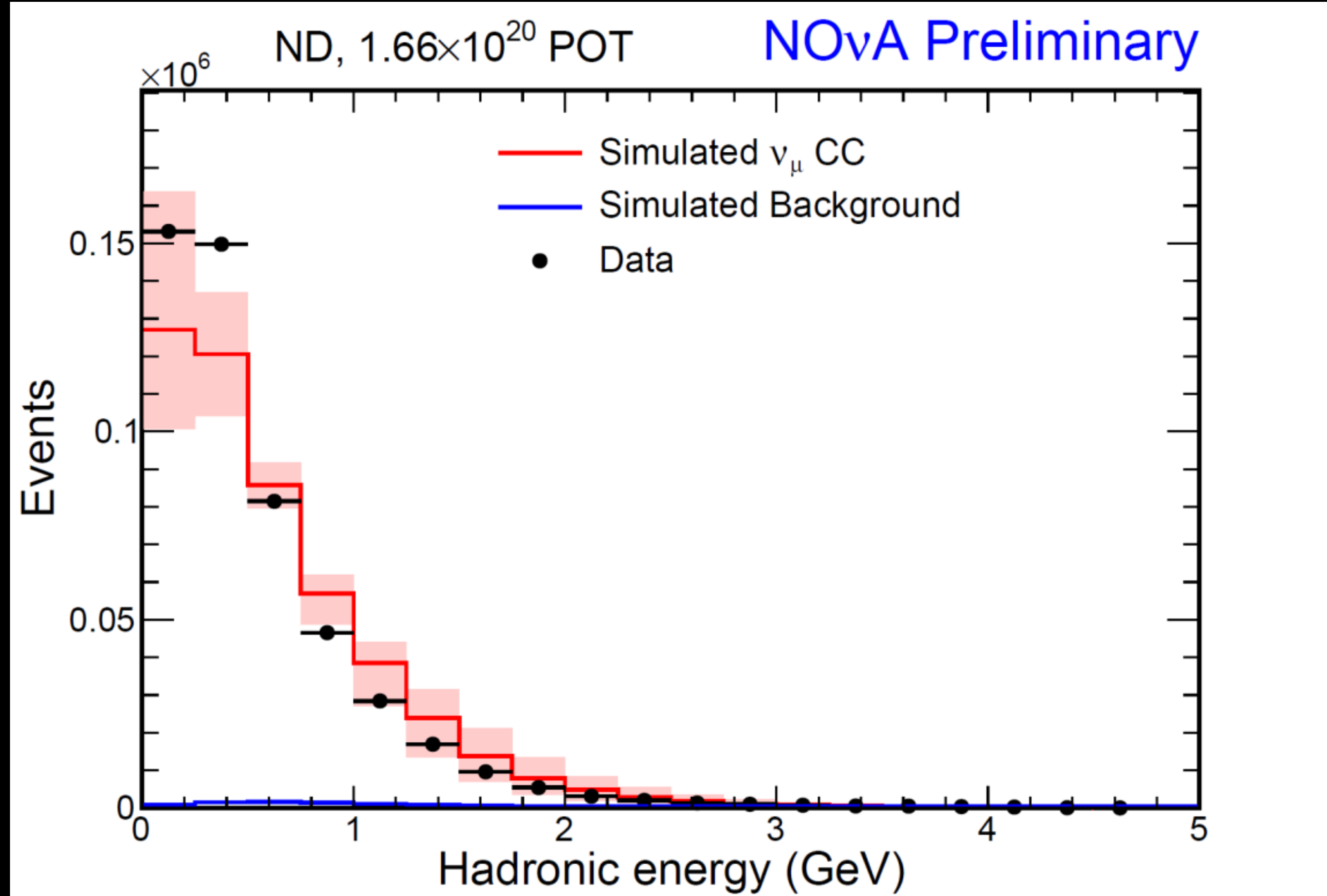

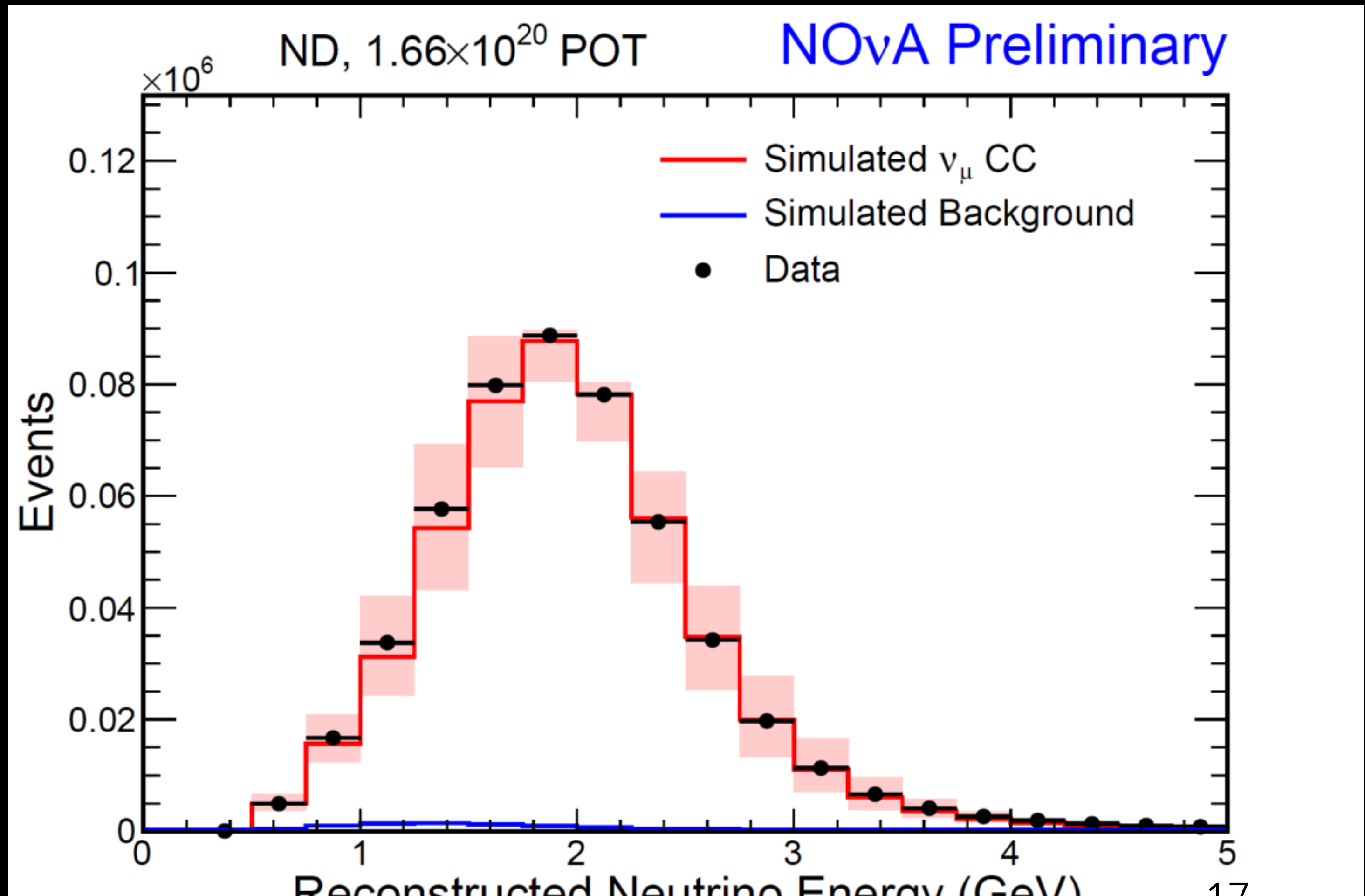

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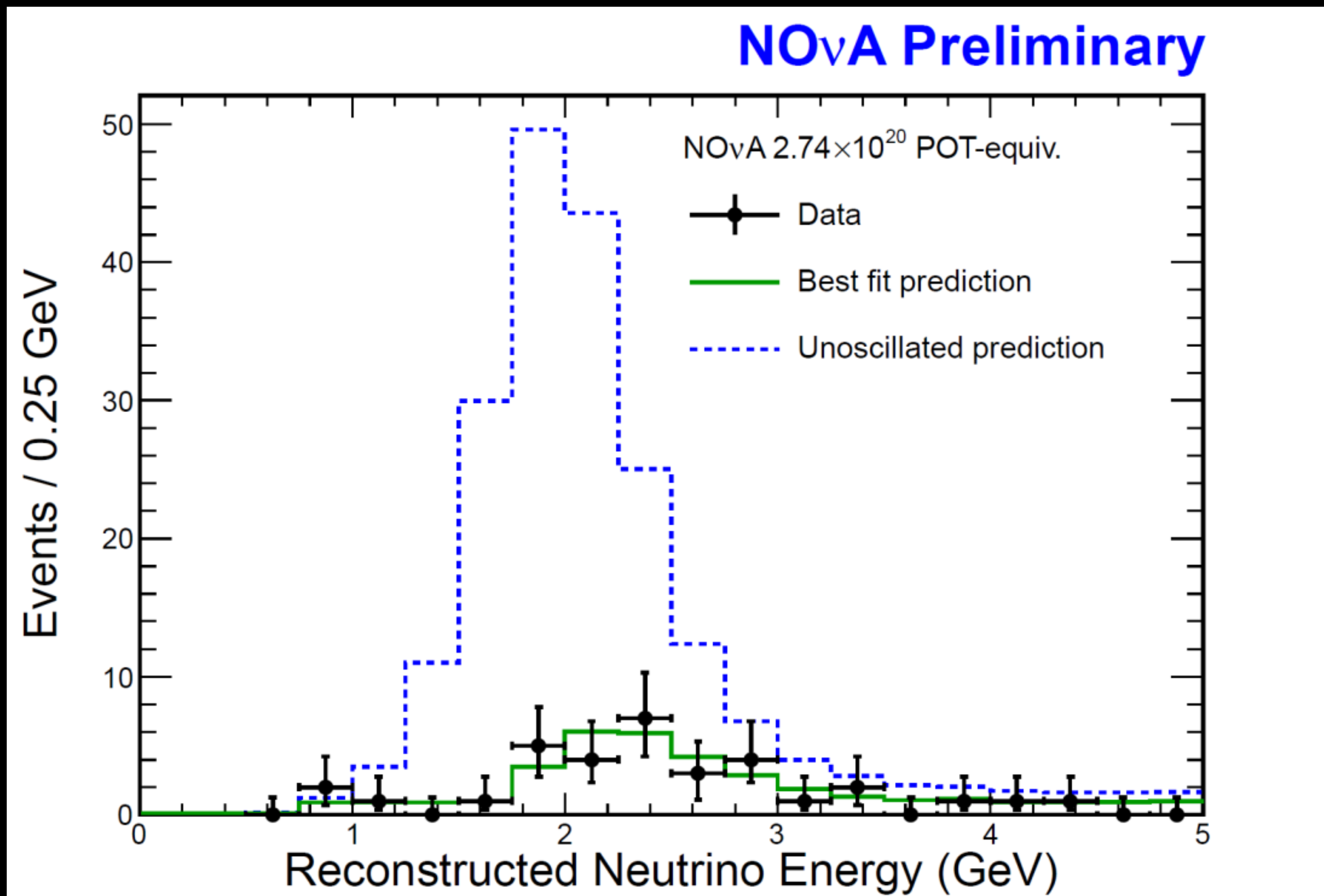
MUON NEUTRINO SELECTED SPECTRUM



- We expect 201 events before oscillations.
- We observe 33 events.

MUON NEUTRINO DISAPPEARANCE RESULTS

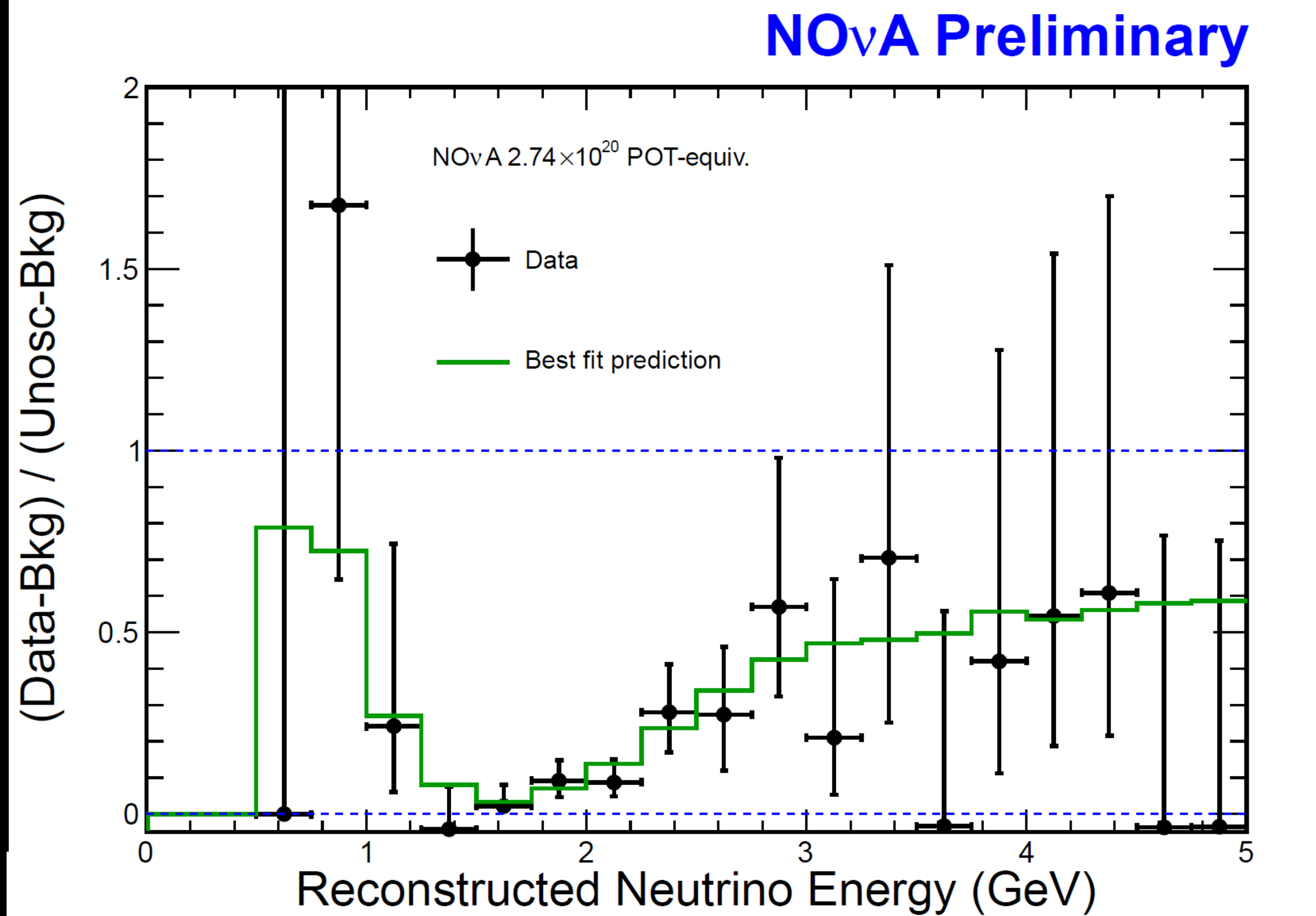
- The spectrum is matched **beautifully** by the oscillation fit.
- Systematic uncertainties included in the fit as nuisance parameters:
    - Hadronic neutrino energy, neutrino flux, absolute and relative normalization, neutrino interactions, NC background rate, multiple calibration and oscillation parameters.

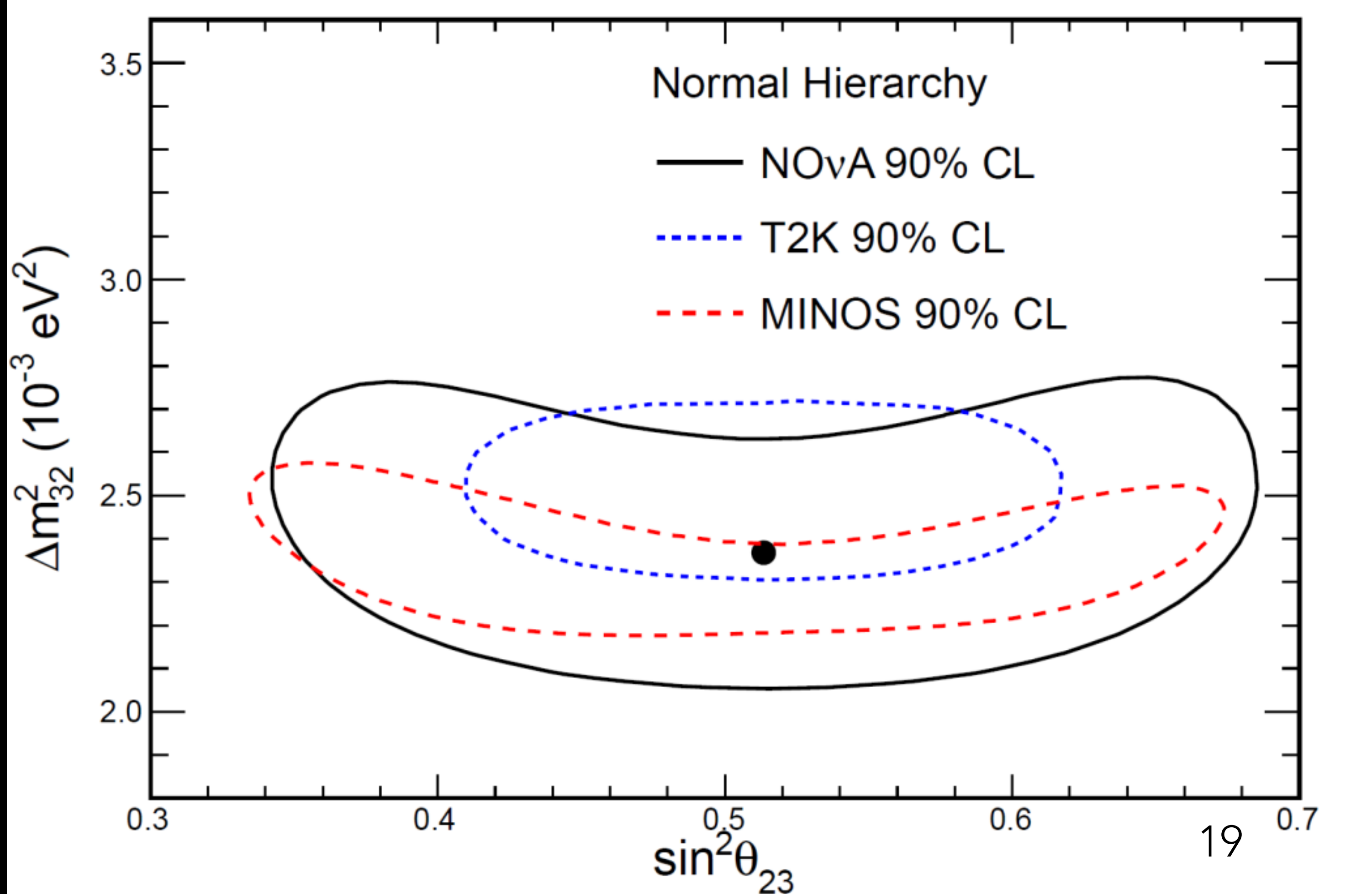
$$\Delta m^2_{32} = +2.37^{+0.16}_{-0.15} \text{ [normal ordering]}$$

$$\Delta m^2_{32} = -2.40^{+0.14}_{-0.17} \text{ [inverted ordering]}$$

$$\sin^2\theta_{23} = 0.51 \pm 0.10$$

COMPELLING MEASUREMENT WITH 7.6% OF NOMINAL EXPOSURE





ELECTRON NEUTRINO APPEARANCE

- The probability of ν_e appearance in a ν_μ beam:

$$A \equiv \frac{G_f n_e L}{\sqrt{2}\Delta} \approx \frac{E}{11\ \mathrm{GeV}}$$

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1)^2} \qquad \Delta \equiv \frac{\Delta m^2_{31} L}{4E}$$

$$+2\alpha \sin\theta_{13}\cos\delta \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \cos\Delta$$

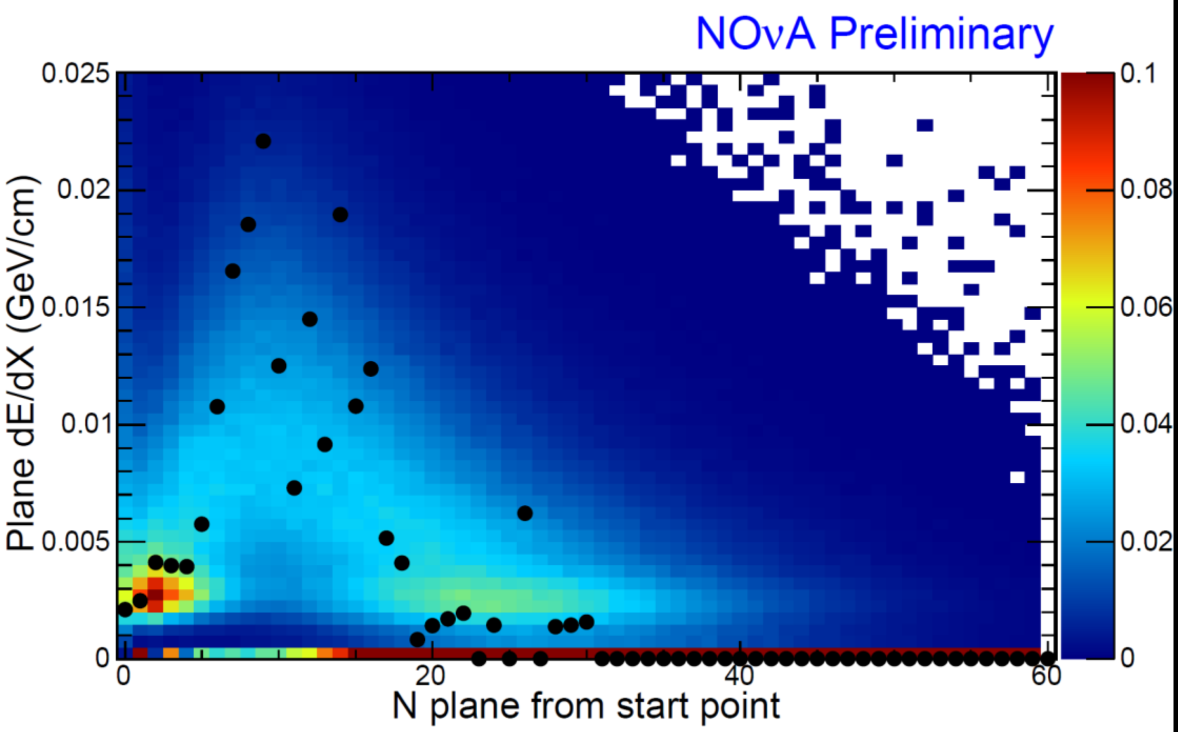
$$-2\alpha \sin\theta_{13}\sin\delta \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \sin\Delta$$

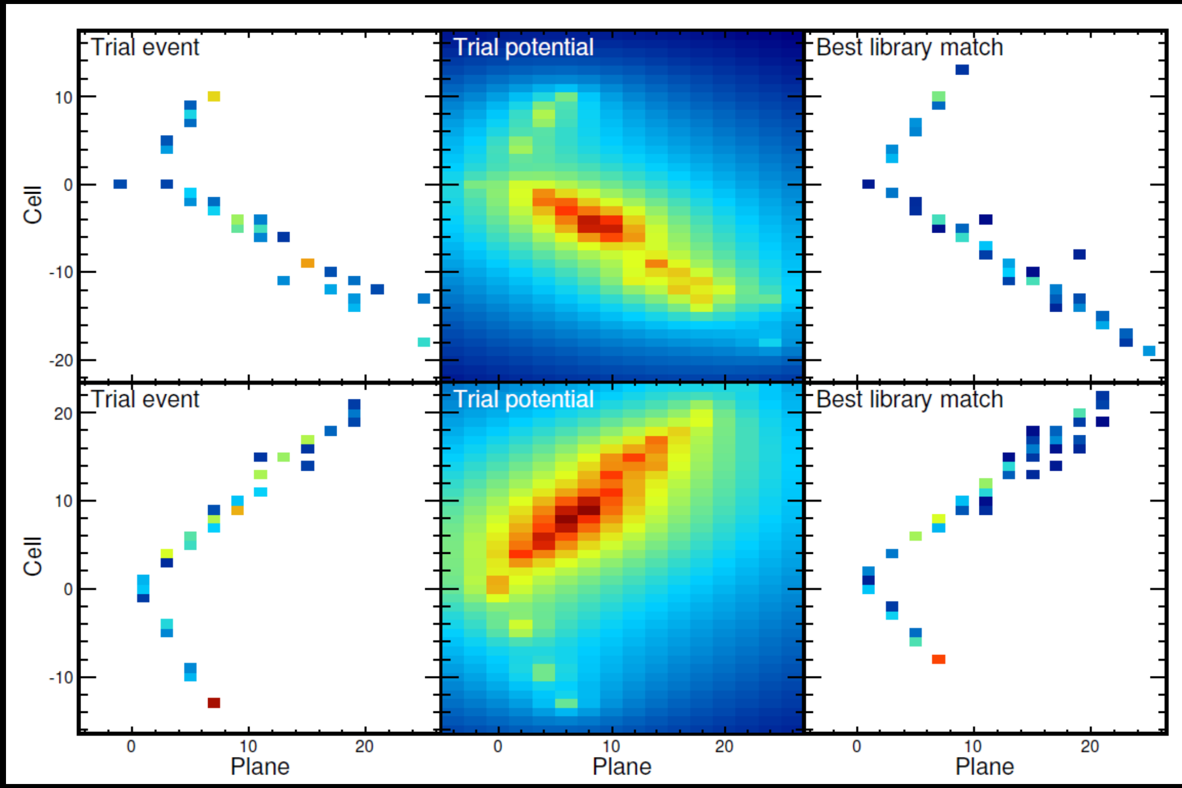
- Searching for ν_e events in NOvA, we can access **$\sin^2(2\theta_{13})$**.
- Probability depends not only on **θ_{13} but also on δ_{CP}** which might be the key to matter anti-matter asymmetry of the universe.
- Probability is enhanced or suppressed due to **matter effects** which depend on the mass hierarchy i.e. the sign of $\Delta m^2_{31} \sim \Delta m^2_{32}$ as well as neutrino vs anti-neutrino running.

NOVA PROBES THE MASS HIERARCHY AND CP VIOLATION SPACE

ELECTRON NEUTRINO SELECTION

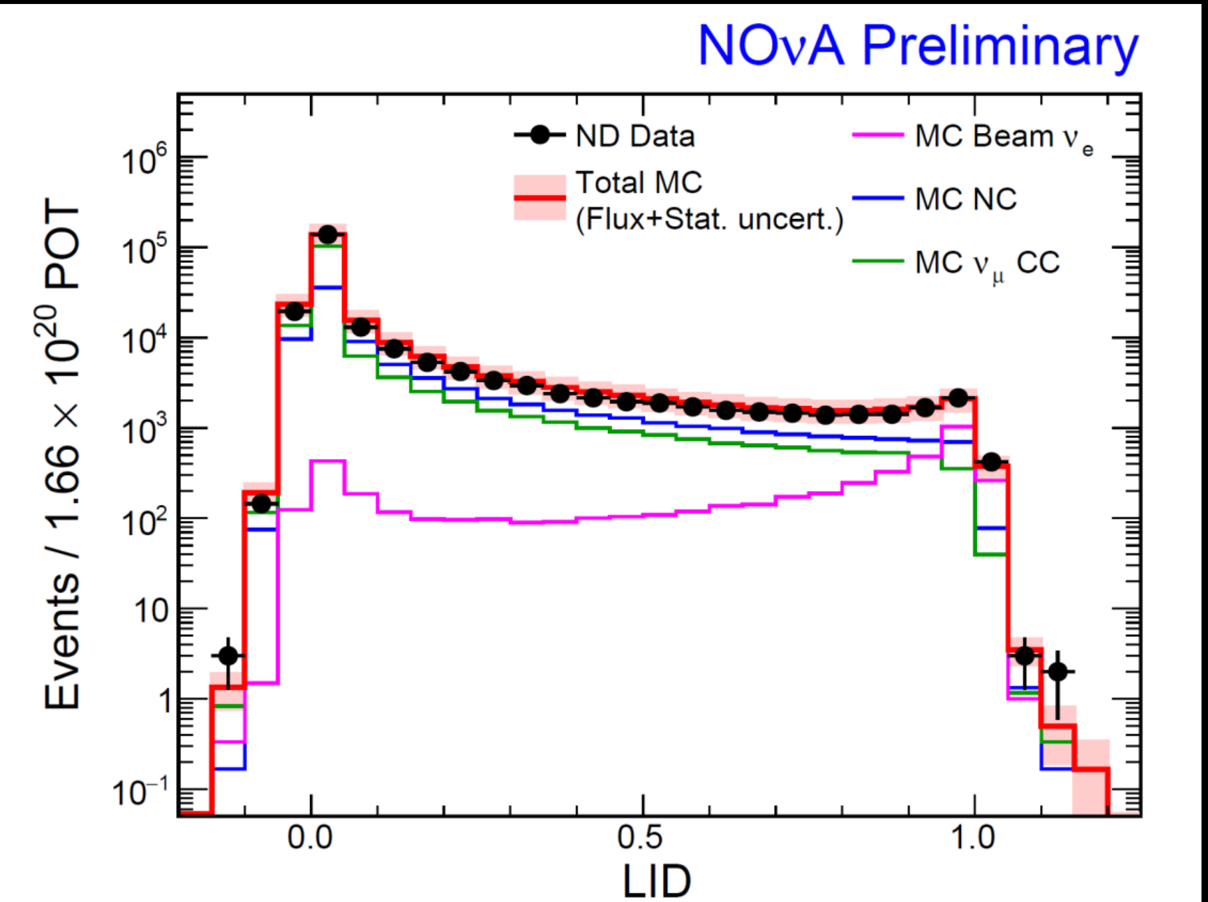
- Two particle ID algorithms based on pattern recognition techniques have been developed:
  - **LID**: evaluates the leading shower longitudinal and transverse dE/dx profiles against probability density functions for e/μ/π/p particles hypotheses. Uses a neural net.
  - **LEM**: evaluates entire the event topologies against a large Monte Carlo library of signal and background events. Assigns identification to trial event according to top matches in library.
- Good separation of electron neutrino signal from background including cosmic background.

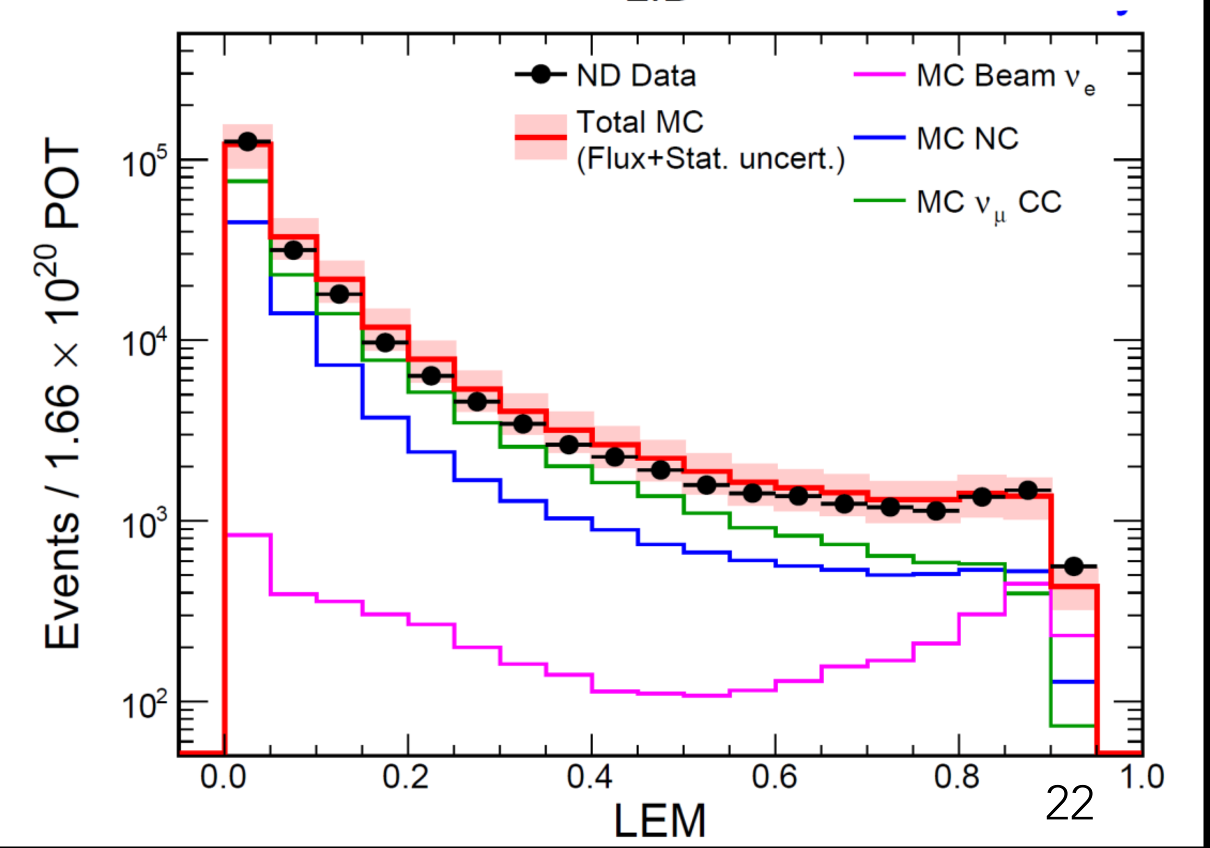




ELECTRON NEUTRINO SELECTION

- Two particle ID algorithms based on pattern recognition techniques have been developed:
  - **LID**: evaluates the leading shower longitudinal and transverse dE/dx profiles against probability density functions for various particles hypothesis. Uses a neural net.
  - **LEM**: evaluates entire the event topologies against a large Monte Carlo library of signal and background events. Assigns characteristics according to top matches.
- Identical performance. Signal efficiency relative to containment cuts: 35%. After all selection, 0.7% of NC events remain, relative to those after containment. Expected overlap in LID and LEM signal samples: 62%.





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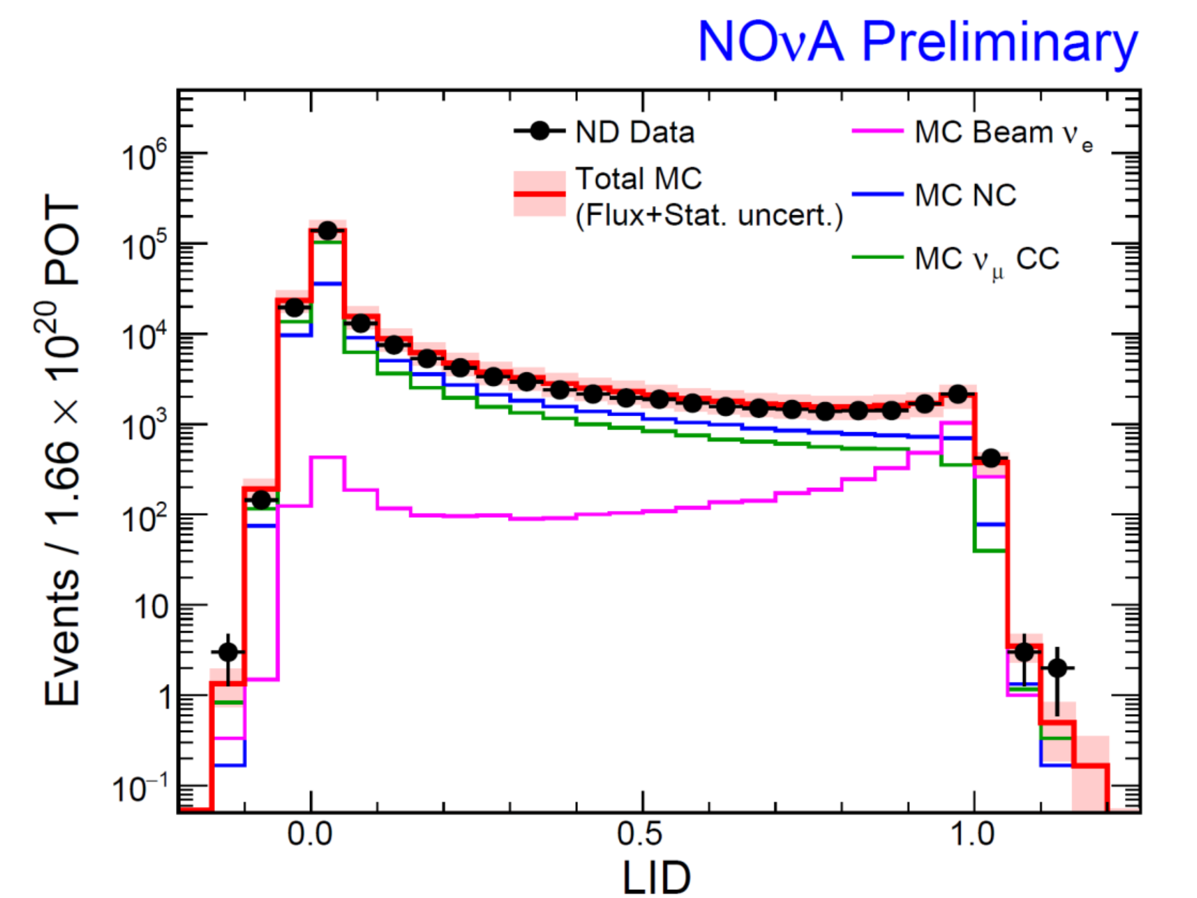
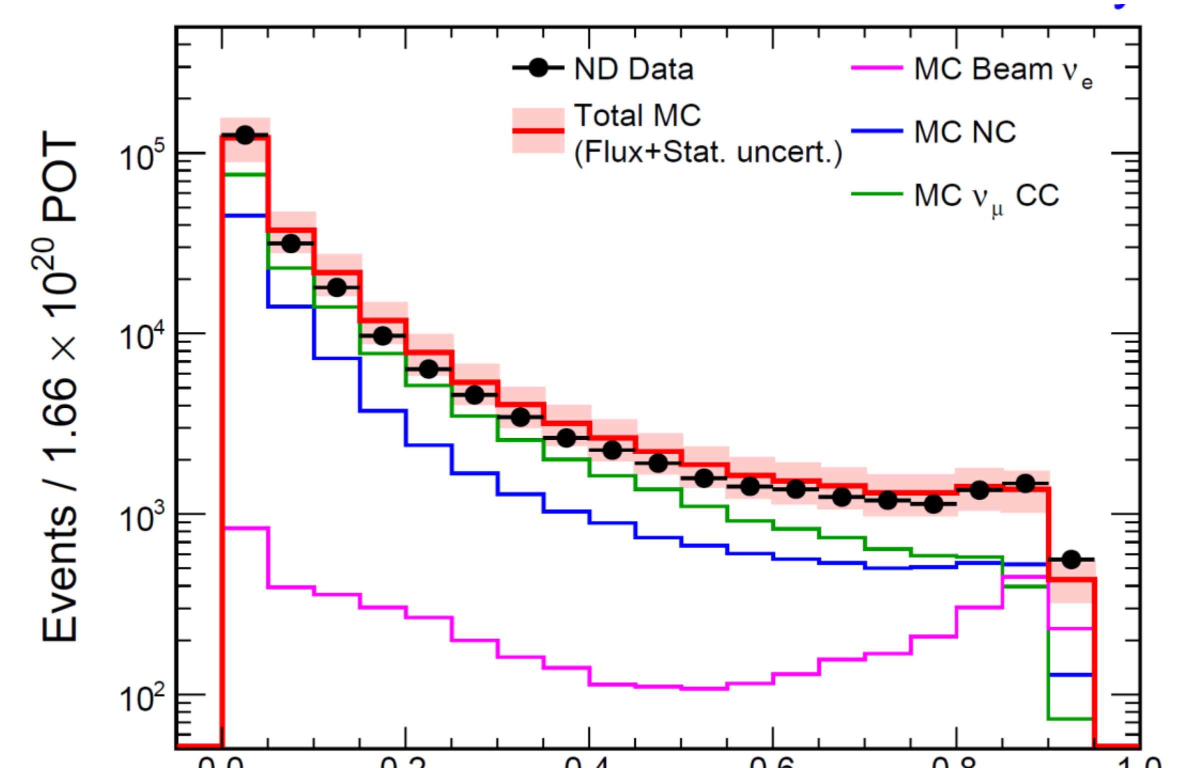
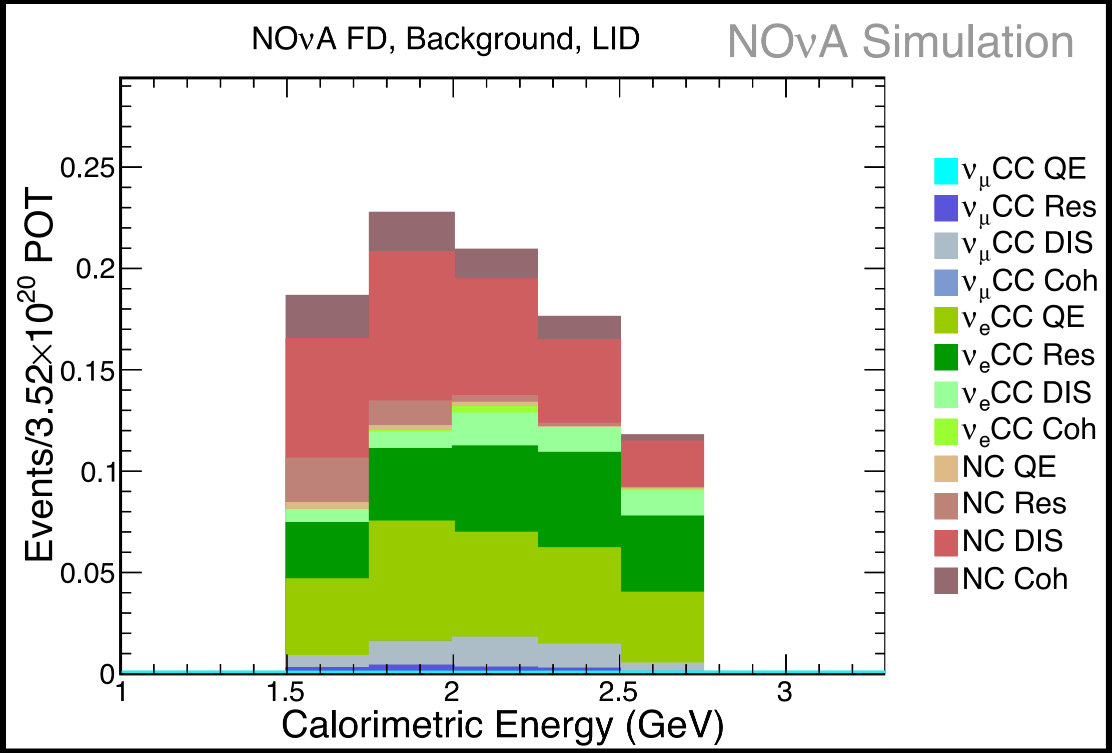
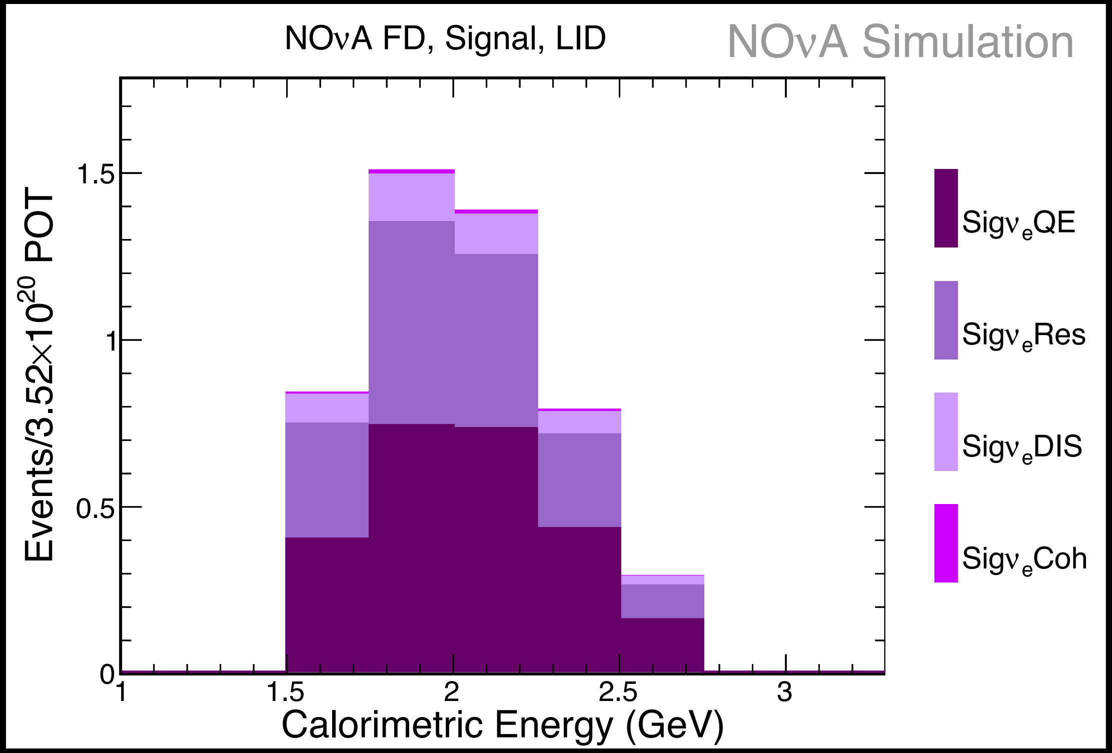
  - **LEM**: evaluates entire the event topologies against a large Monte Carlo library of signal and background events. Assigns characteristics according to top matches.
- PRIOR TO UNBLINDING DECIDED TO SHOW BOTH RESULTS AND USE **LID** AS PRIMARY SELECTOR

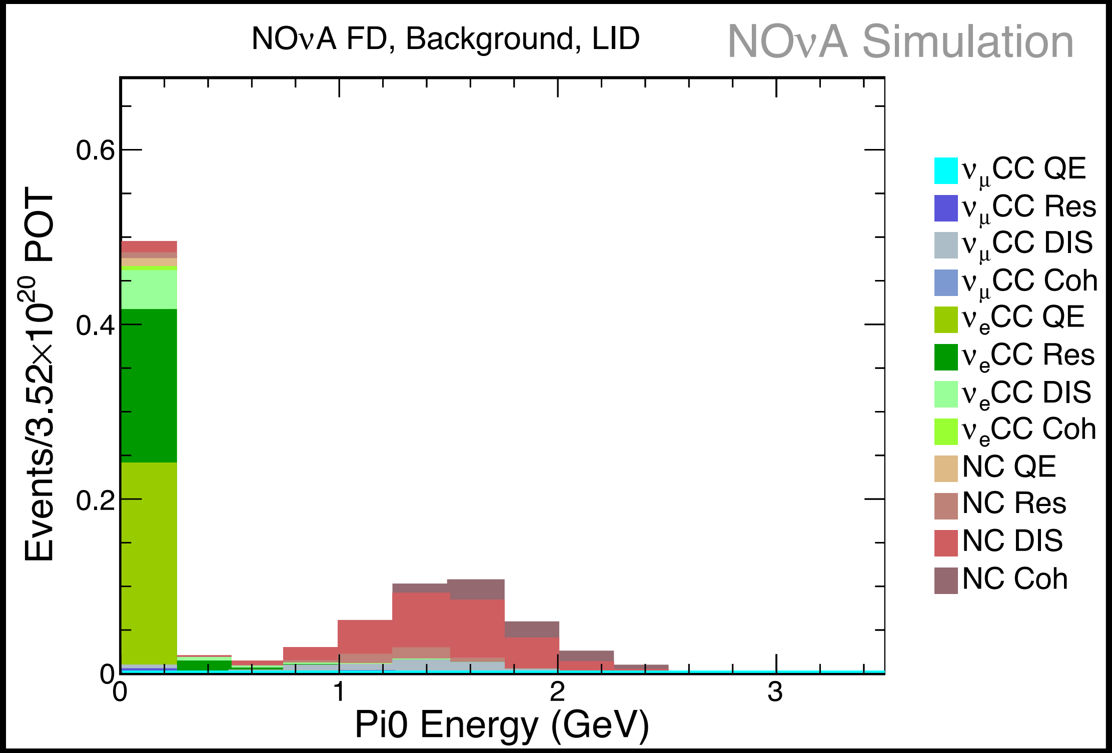




ELECTRON NEUTRINO SELECTION



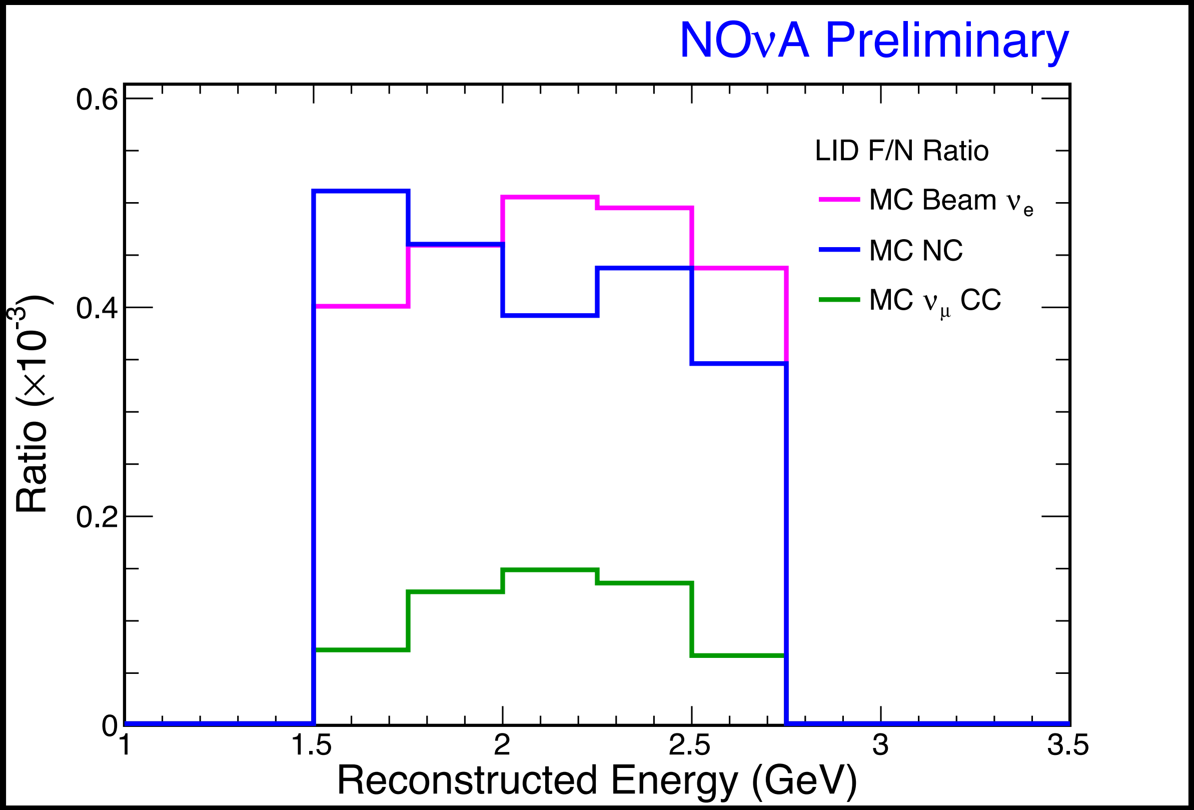


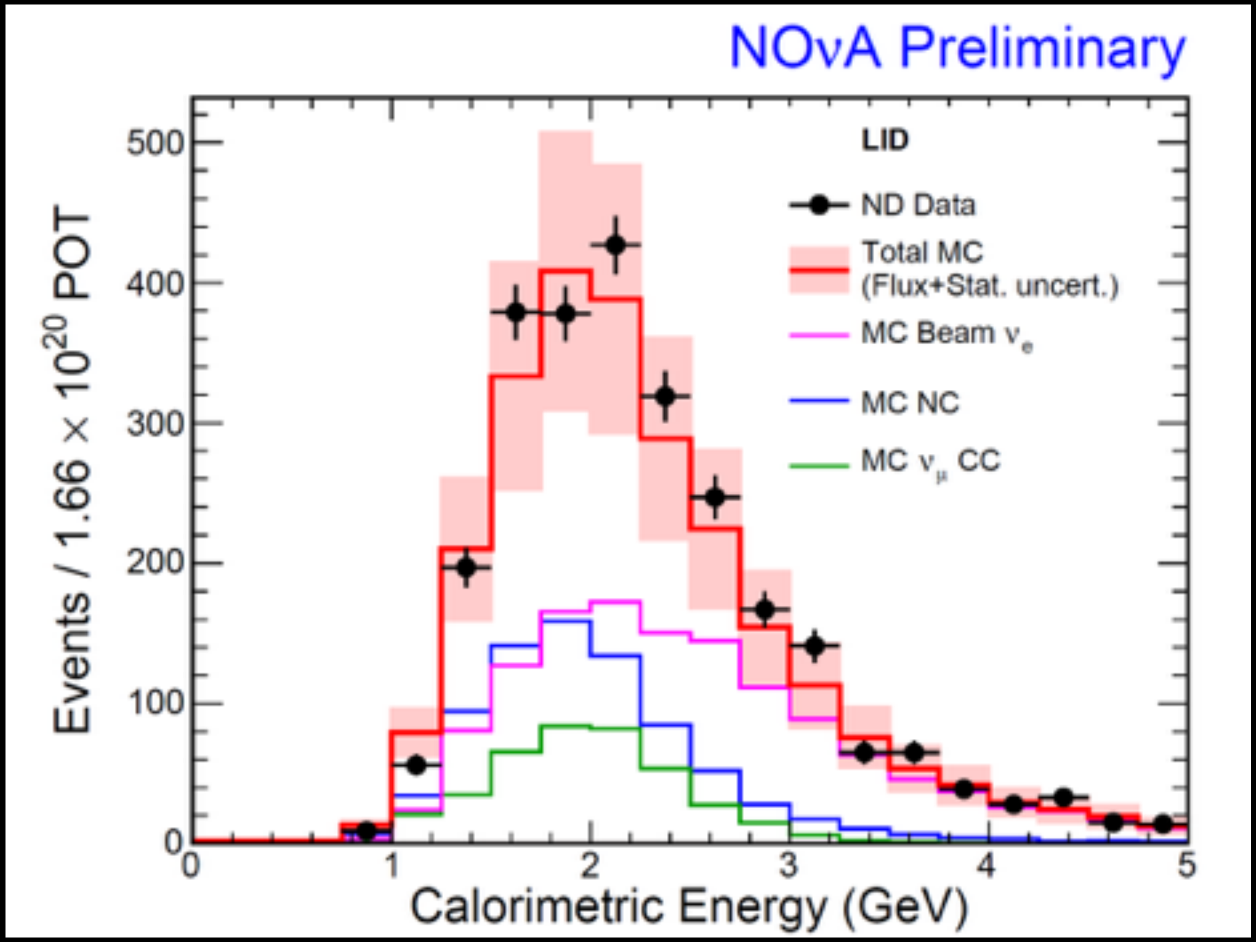


- Selected background in the FD dominated dominated by electron neutrinos from beam contamination and NC DIS.
  - Most of the latter have a π^0 with energy similar to expected signal.
- Signal dominated by quasi-elastic and resonance interactions. Expect minimal impact from hadronic system.

PREDICTING THE BACKGROUND IN THE FD

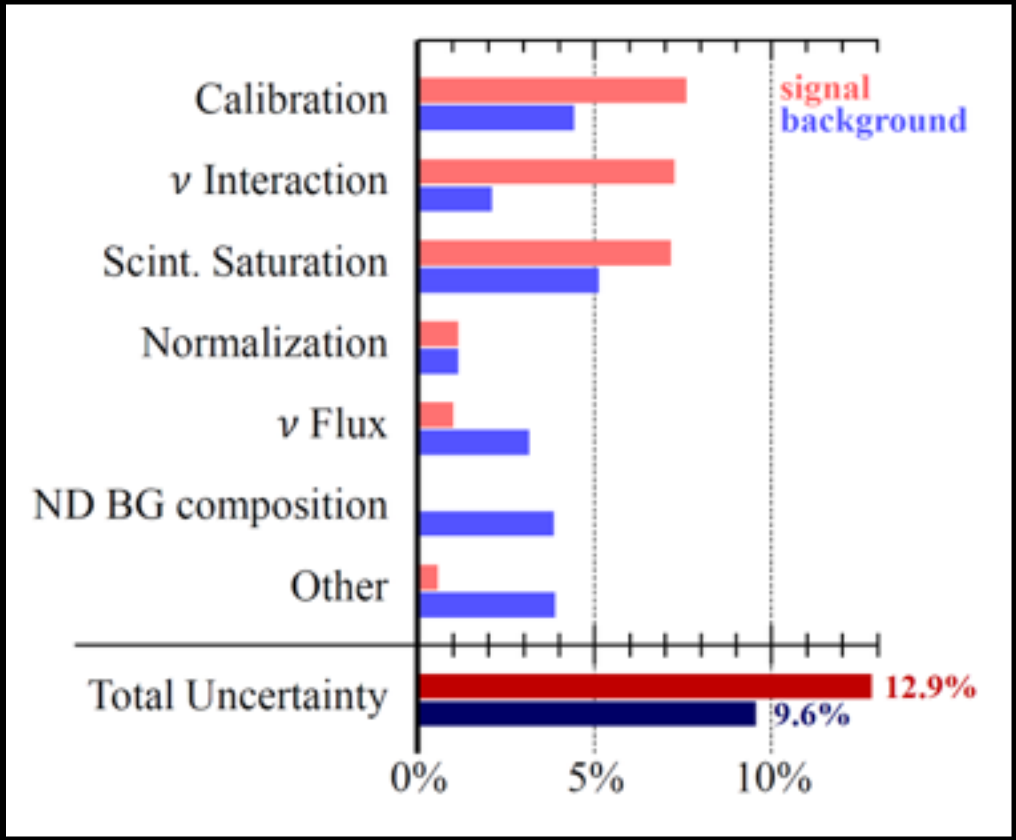
- Calorimetric energy after electron neutrino selection (shown for LID) shows good agreement.



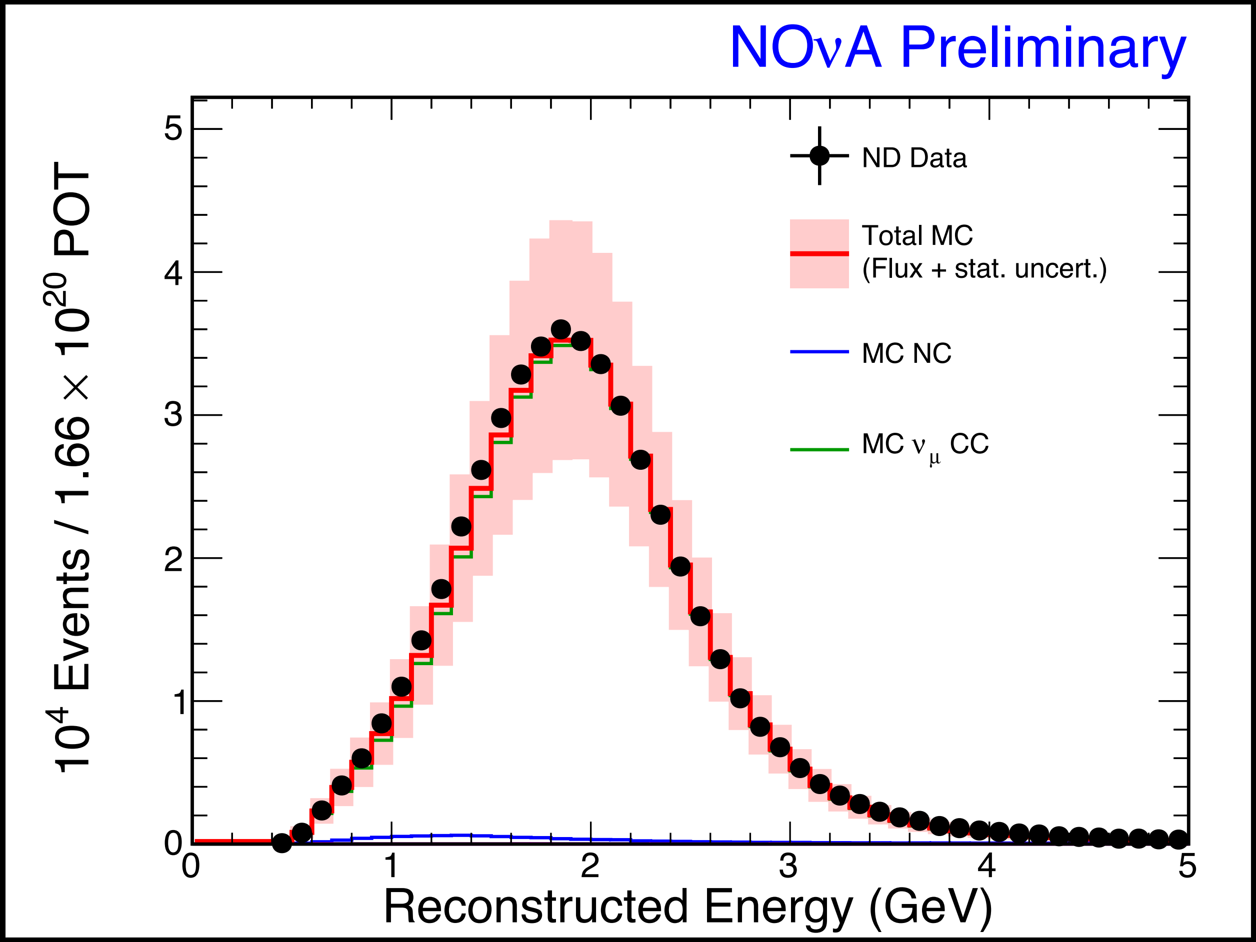


- ND data is translated to FD background expectation in each energy bin, using Far/Near ratios from simulation.
- A small 5% excess in data is observed in the ND which is used as a correction to the FD background prediction.

PREDICTING THE SIGNAL IN THE FD



- FD signal expectation is predicted using the ND-selected ν_μ CC spectrum using same technique as for muon neutrino disappearance.

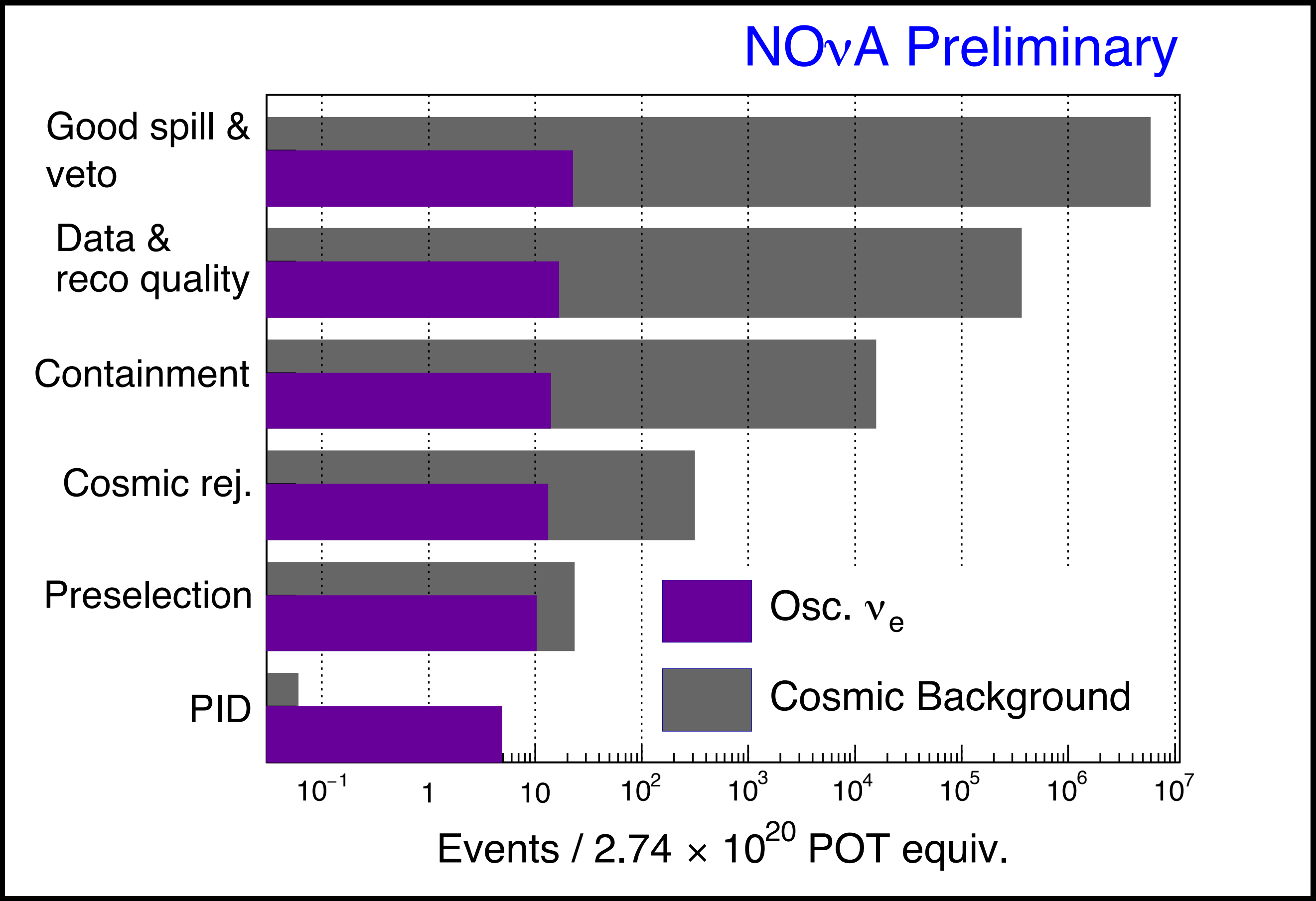


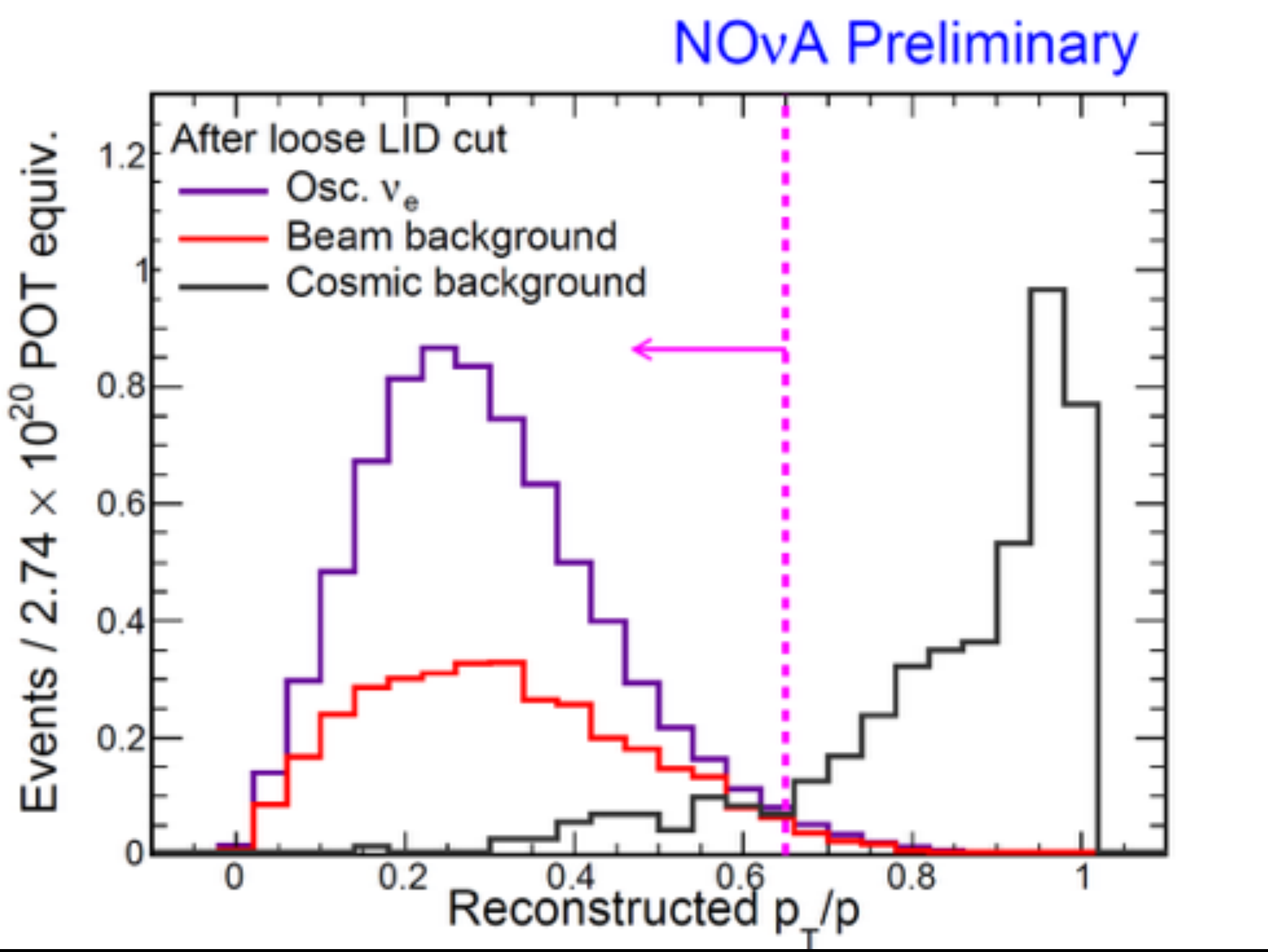
- Most systematics are assessed by modifying the Far/Near simulated ratios and calculating the variation in the prediction both for signal and background.

SEVERAL INDEPENDENT EM SAMPLES SHOW GOOD DATA/MC AGREEMENT

COSMIC REJECTION FOR ELECTRON NEUTRINOS

- Containment and topological cuts such as removing events with large p_T/p remove significant factors of this background.
- The electron neutrino selectors themselves provide the remaining level of rejection to achieve 10^8 removal of cosmic ray interactions.
- Measurement of background on out-of-time spill data.





EXPECTED COSMIC BACKGROUND: 0.06 EVENTS

BACKGROUND AND SIGNAL PREDICTIONS

- Background predictions for both selectors are about 1 count each, 10% systematic. Few percent dependence on oscillation parameters.
- Dominated by beam electron neutrinos and NC.
- Cosmic background comparable to smallest beam backgrounds.

PID	total bkg	ν_e CC bkg	NC bkg	ν_μ CC bkg	ν_μ CC bkg	cosmic bkg
LID	**0.94±0.09**	0.46	0.35	0.05	0.02	0.06
LEM	**1.00±0.11**	0.46	0.40	0.06	0.02	0.06

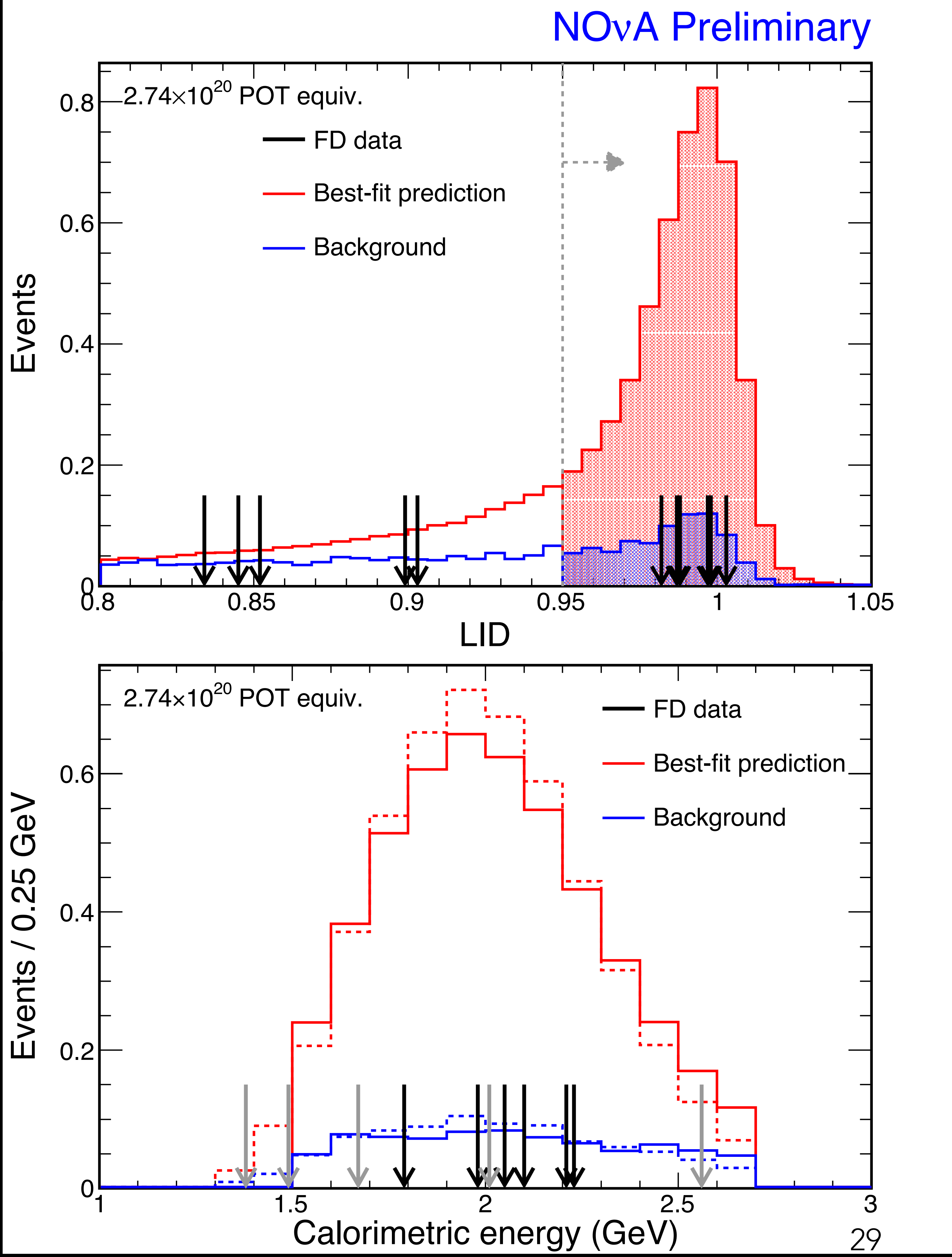
- Signal prediction depends on oscillation parameters, for LID (similar for LEM), the extremes are:

6 ± 0.7 (NH $\delta_{CP}=3\pi/2$)

2 ± 0.3 (IH $\delta_{CP}=\pi/2$)

ELECTRON NEUTRINO SELECTED EVENTS

- LID selects 6 events and LEM selects 11. The expected background in each case is 1 event.
  - **The significance of appearance is 3.3σ (LID) and 5.5σ (LEM).**
- All 6 of LID events are also selected by LEM. The P-value for selecting the combination (11:6/5/0) is 9.2%.
  - Note that LID and LEM have a difference in energy cuts in the low end.
- Other reassuring distributions include time, spatial and angular distributions.



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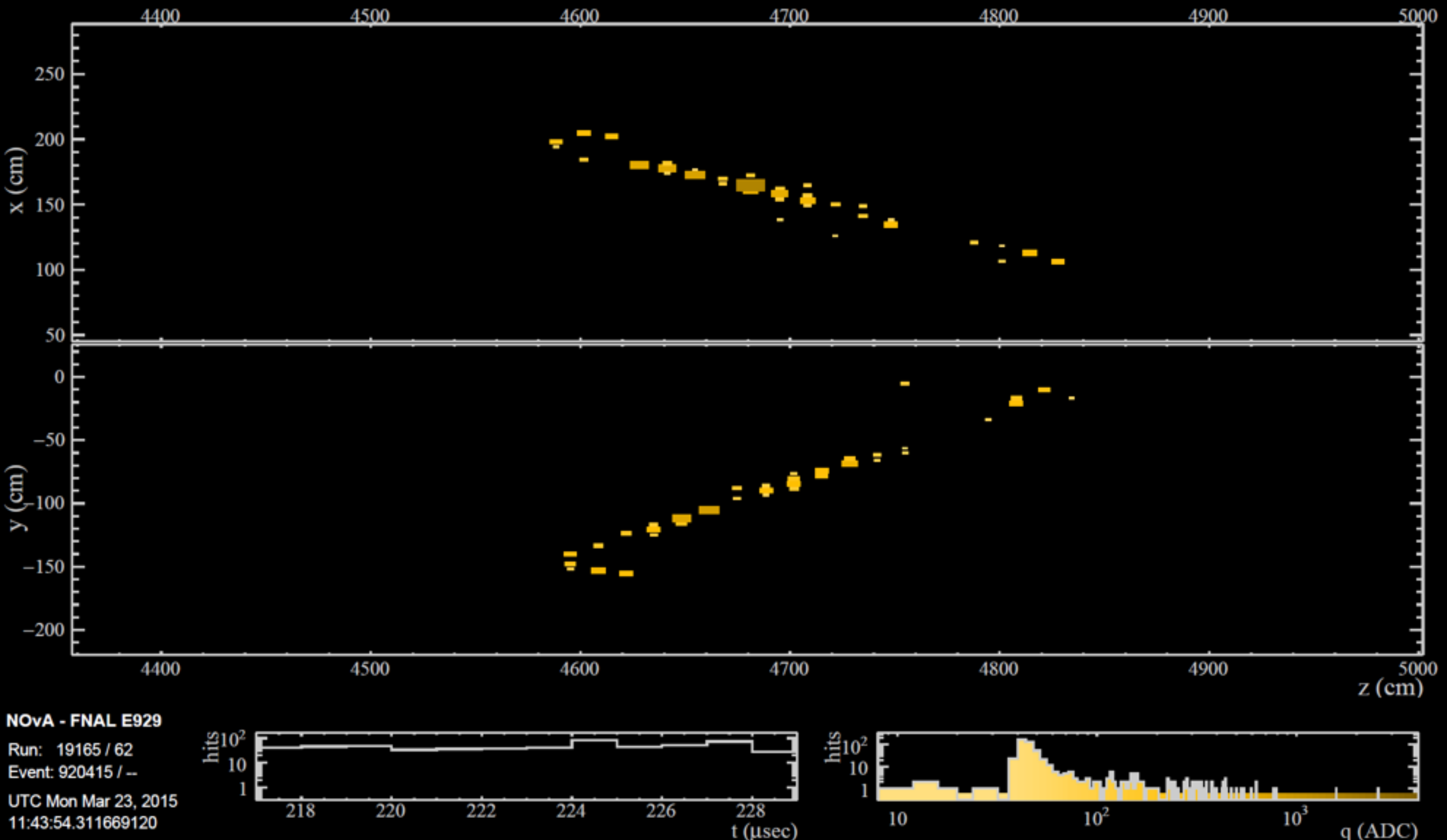
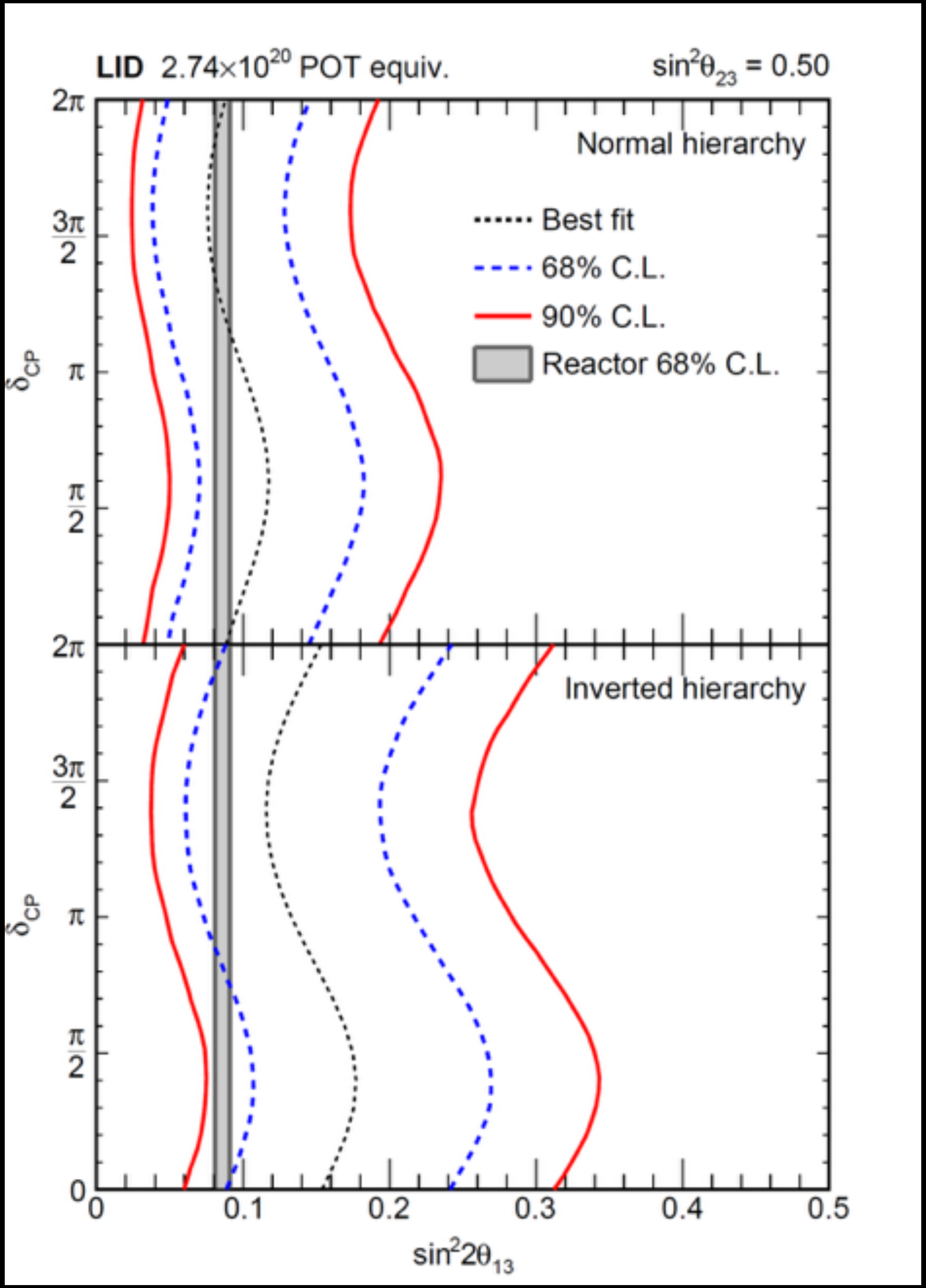


ALL 11 OF THEM ARE ABSOLUTELY GORGEOUS!

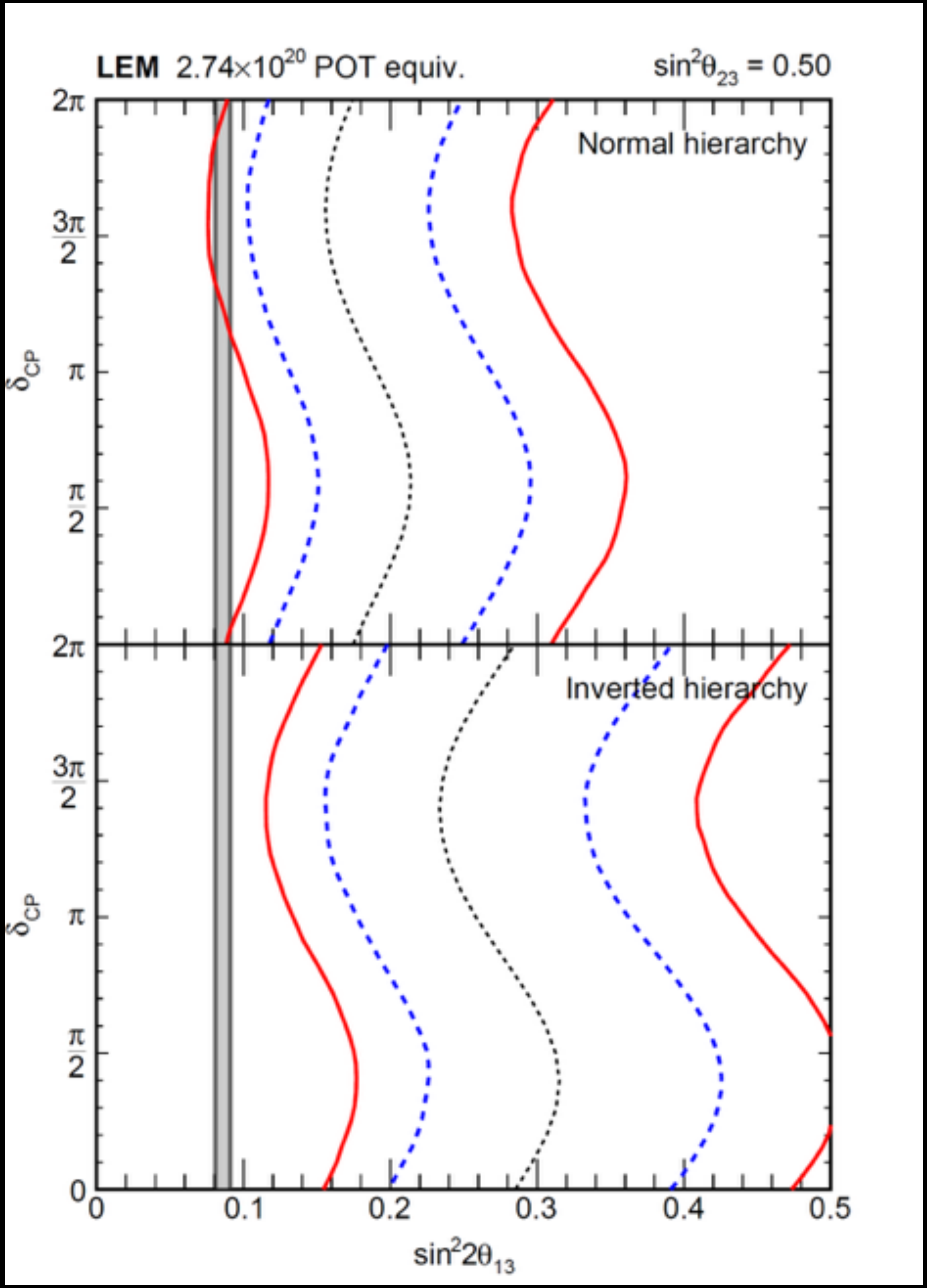
ELECTRON NEUTRINO APPEARANCE RESULTS

- Results show good consistency between NOvA (s-curves) and reactor experiments (gray band) for normal (top) and inverted mass ordering (bottom).
- Agreement is ~1σ better for the normal ordering.
- This plot is for LID selector (n=6).



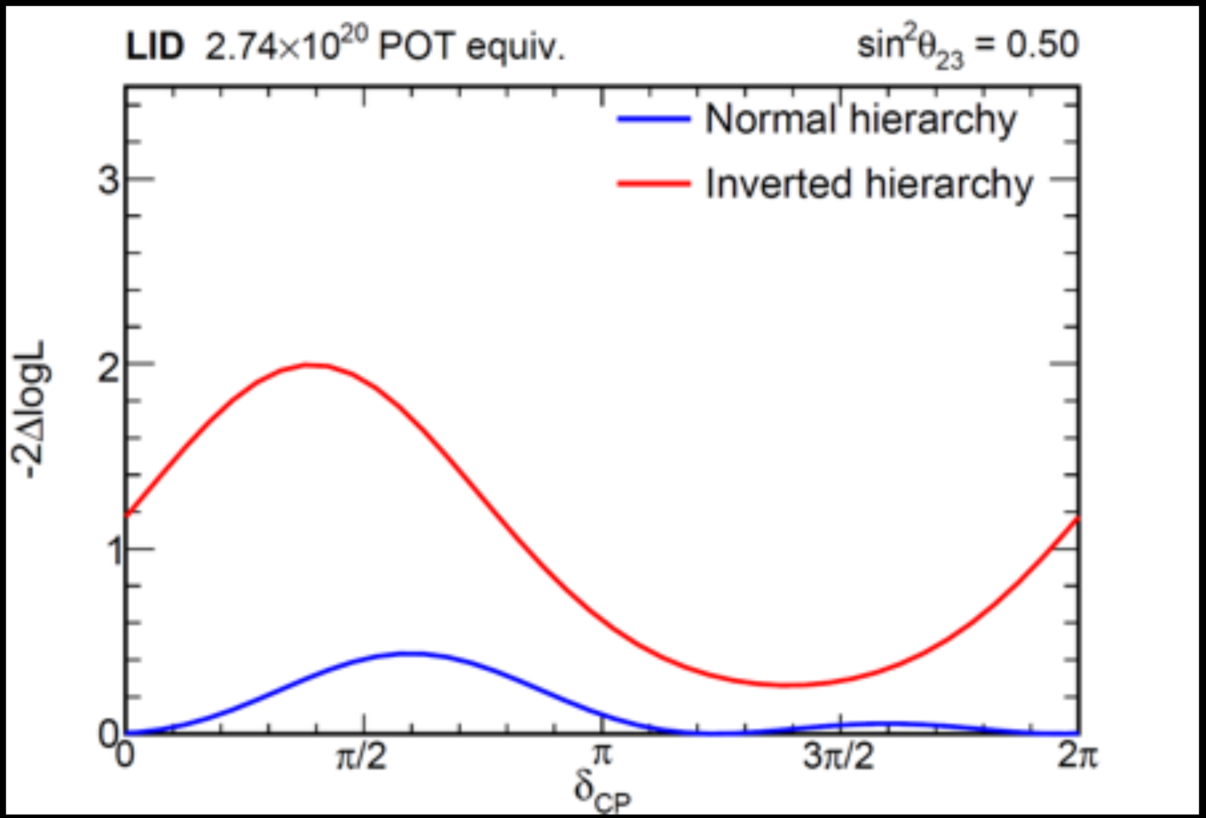
ELECTRON NEUTRINO APPEARANCE RESULTS

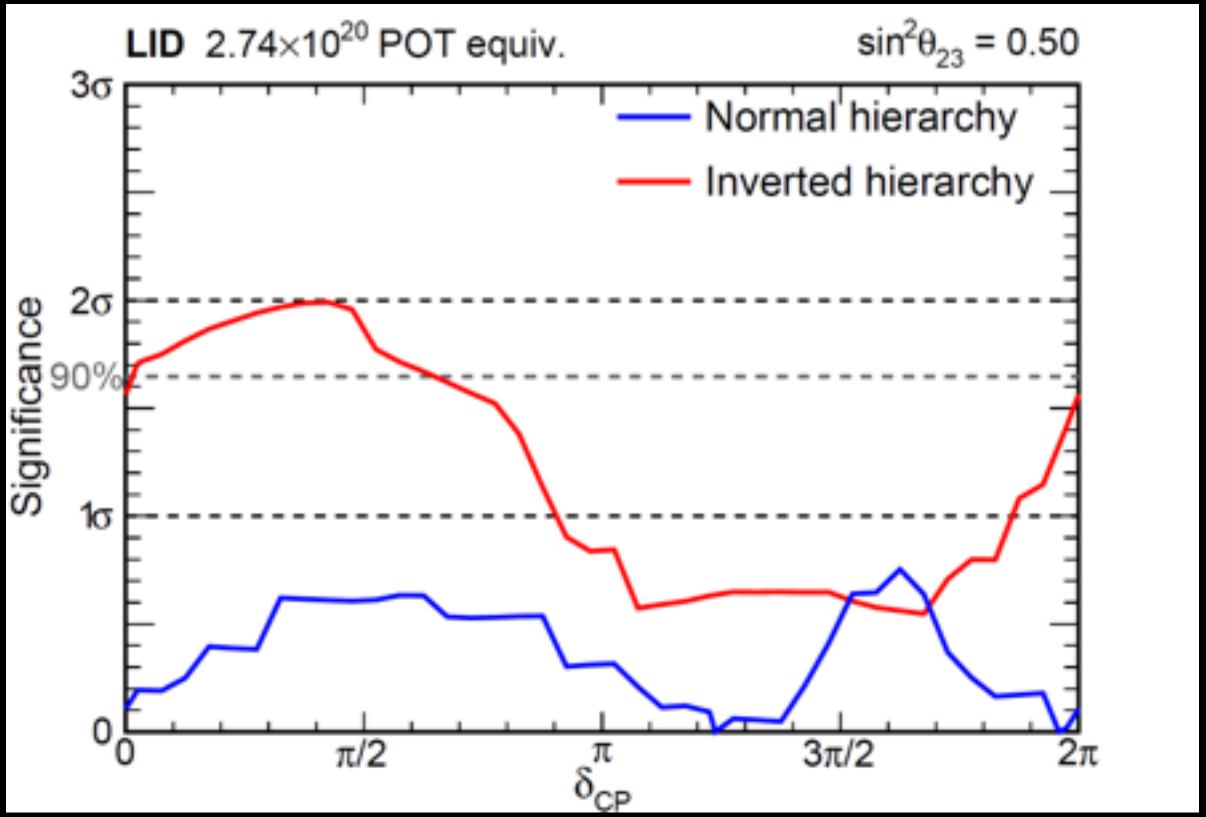
- Results show good consistency between NOvA (s-curves) and reactor experiments (gray band) for normal (top) and inverted mass ordering (bottom).
- Agreement is ~1σ better for the normal ordering.
- For LEM (n=11) the s-curves shift by a factor of 2 to the right increasing tension for the inverted mass ordering.



ELECTRON NEUTRINO APPEARANCE RESULTS

- Taking the reactor measurement of θ_{13} as an input, we can explore compatibility with the mass hierarchy and and δ_{CP} using Feldman-Cousins.
- There is a significant deviation from gaussian limits in this case. Also non-smooth shape due to discreet nature of counting experiment.
- Resulting significances show that at maximal mixing, we disfavor the IH for $\delta \in [\, 0, 0.6\pi \,]$ at 90% C.L. with primary selector.





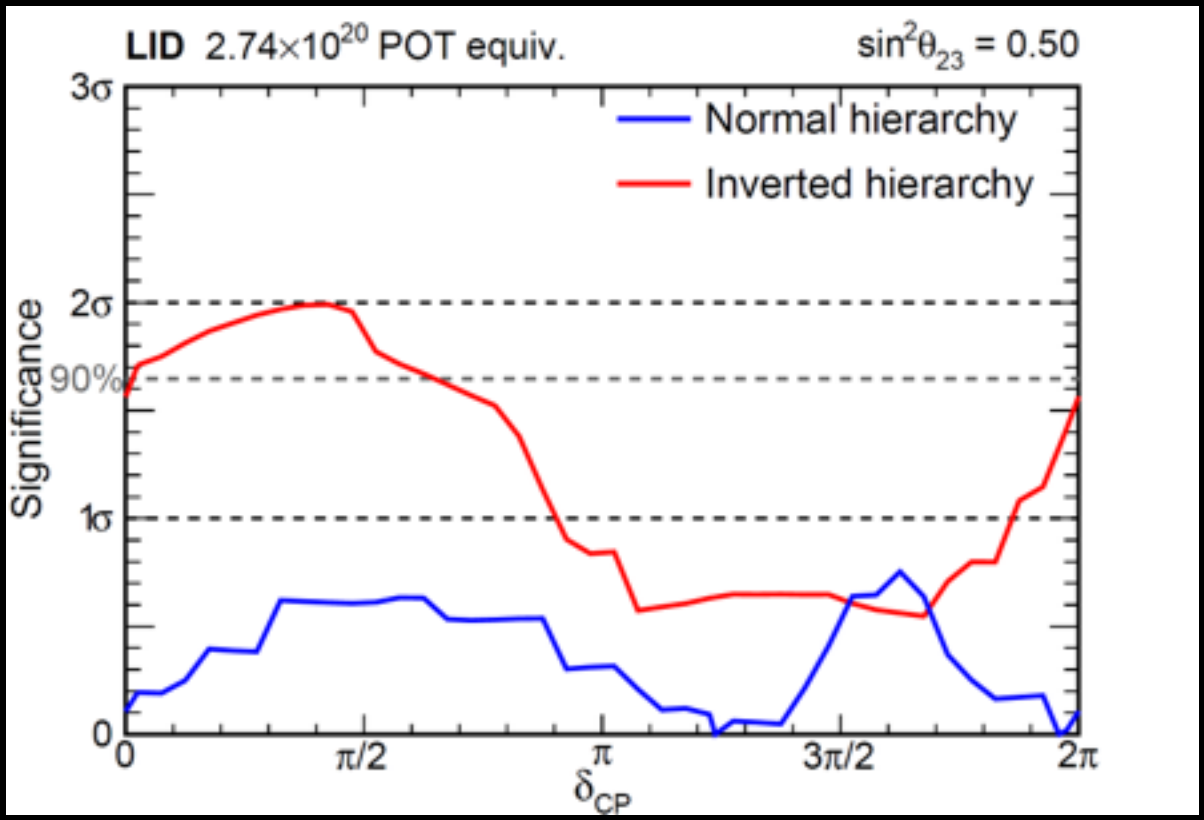
with $\sin^2 2\theta_{13} = 0.086 \pm 0.005$

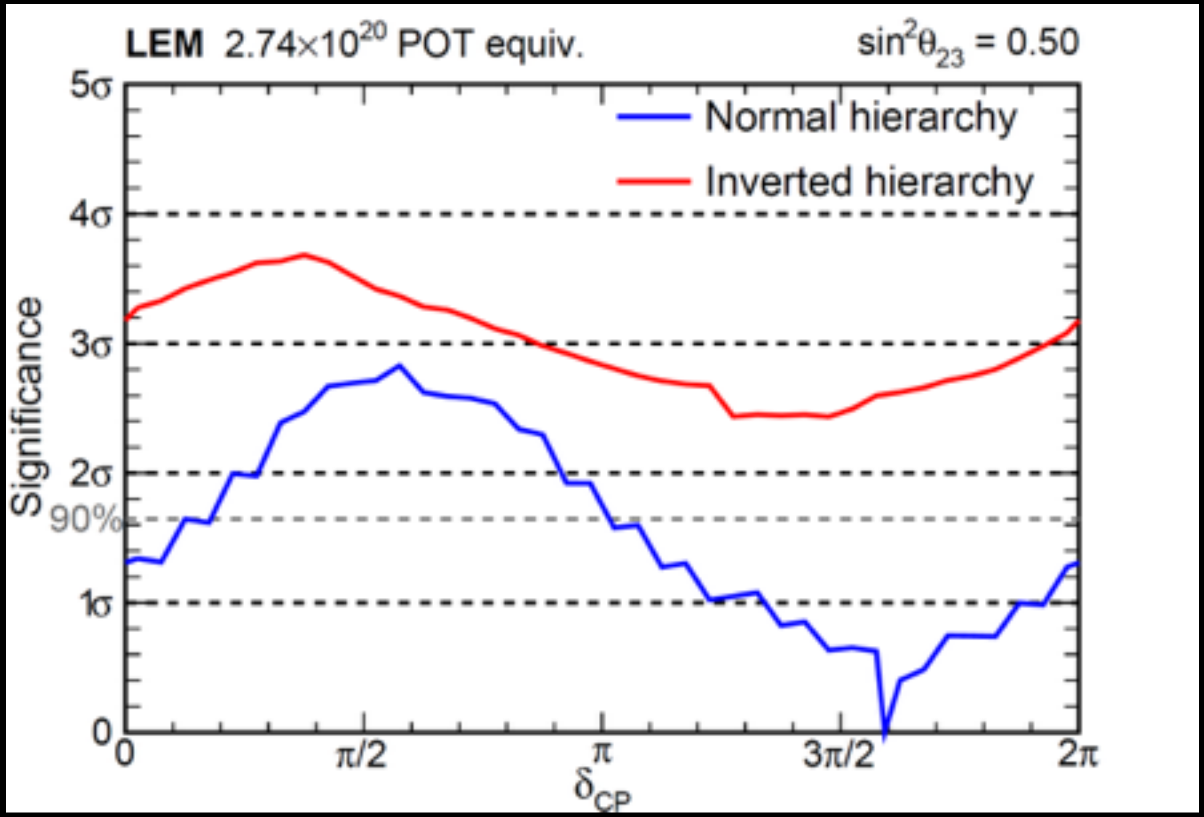
ELECTRON NEUTRINO APPEARANCE RESULTS

- Both selectors prefer normal hierarchy.
- Both selectors prefer δ near $3\pi/2$.
- Given expected correlations, the observed event counts yield a reasonable mutual p-value of 9.2%.
- The specific point IH, $\delta=\pi/2$ is disfavored at 1.6σ (LID) and 3.2σ (LEM)* for $\sin\theta_{23}$ = 0.4-0.6.

CONSISTENT HINTS!

Beware of trials factor of choosing LEM over LID after seeing results.

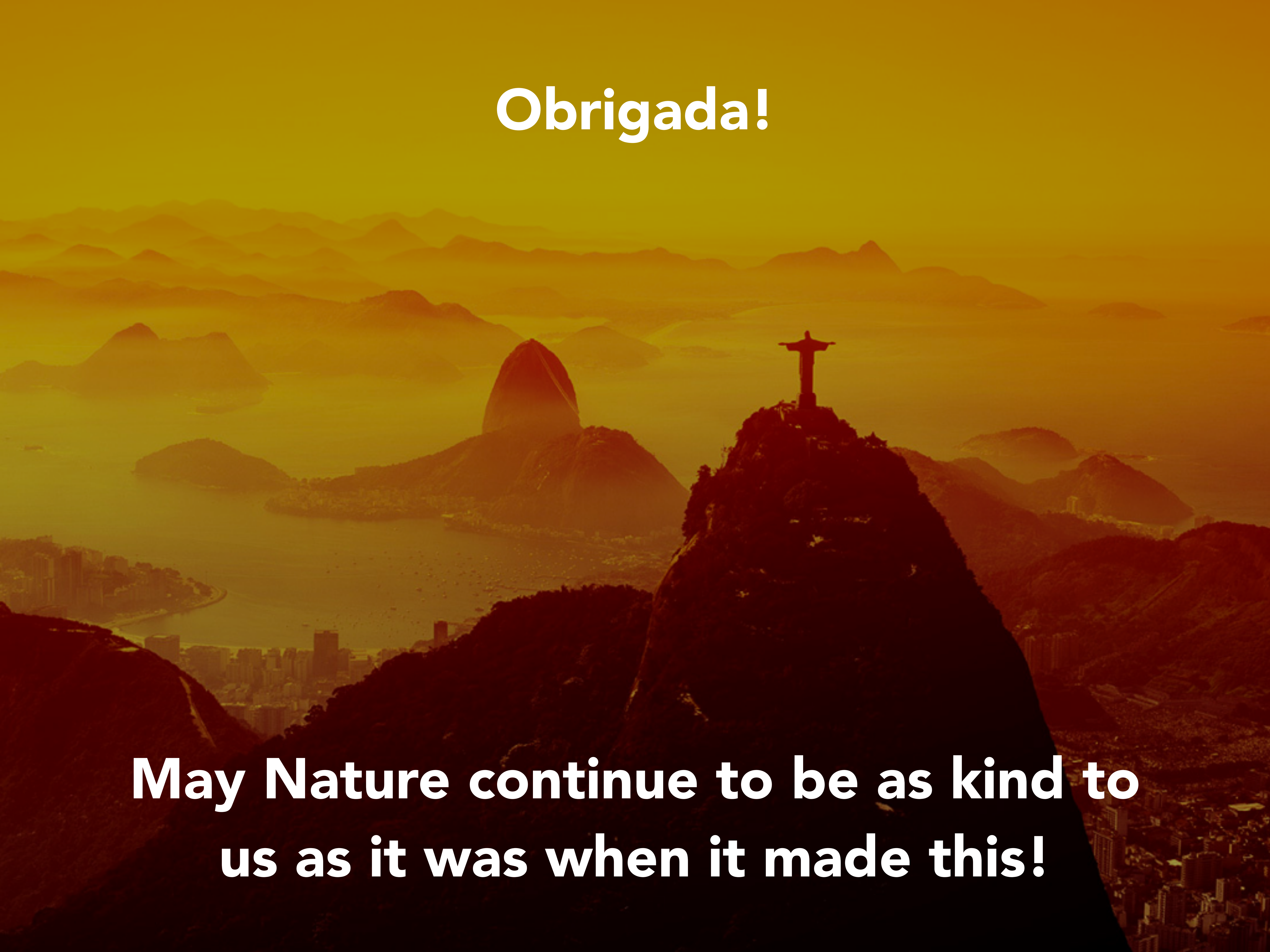




with $\sin^2 2\theta_{13} = 0.086 \pm 0.005$

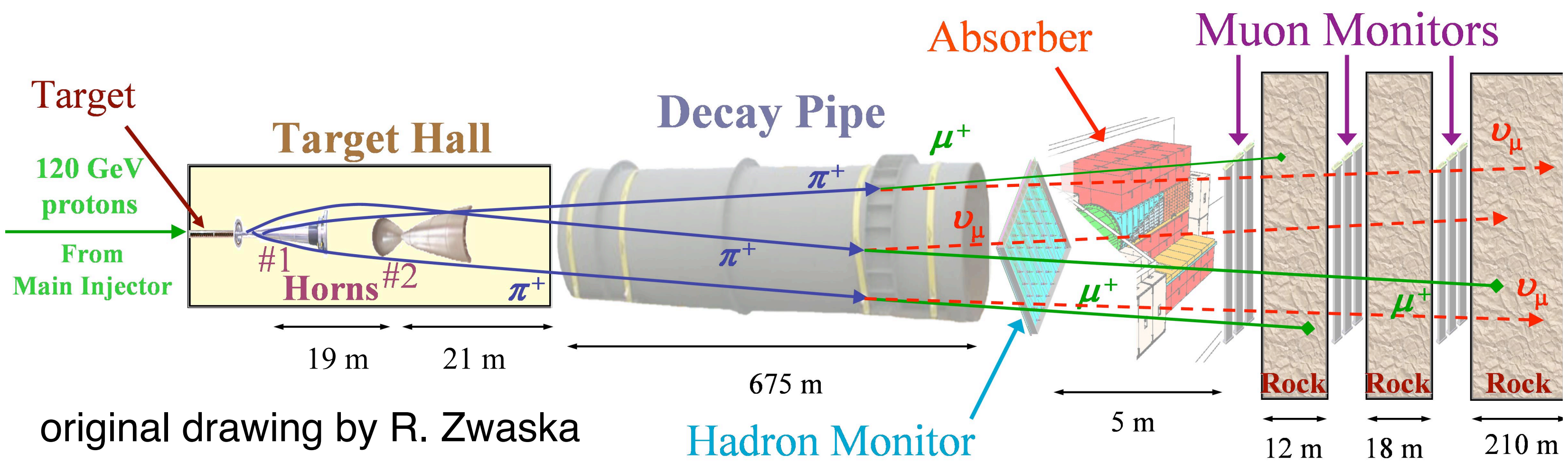
SUMMARY

- NOvA has observed muon neutrino disappearance and electron neutrino appearance with 1/13th of baseline exposure:
  - Obtains 6.5% measurement of atmospheric mass splitting, and θ_{23} measurement consistent with maximal mixing.
  - Observes electron neutrino appearance signal at 3.3σ for primary ν_e selector, 5.5σ for secondary selector.
    - Consistent with hints of a preference for $\pi<\delta_{CP}<2\pi$ normal mass ordering.
- Stay tuned for doubling of the data set by next summer!

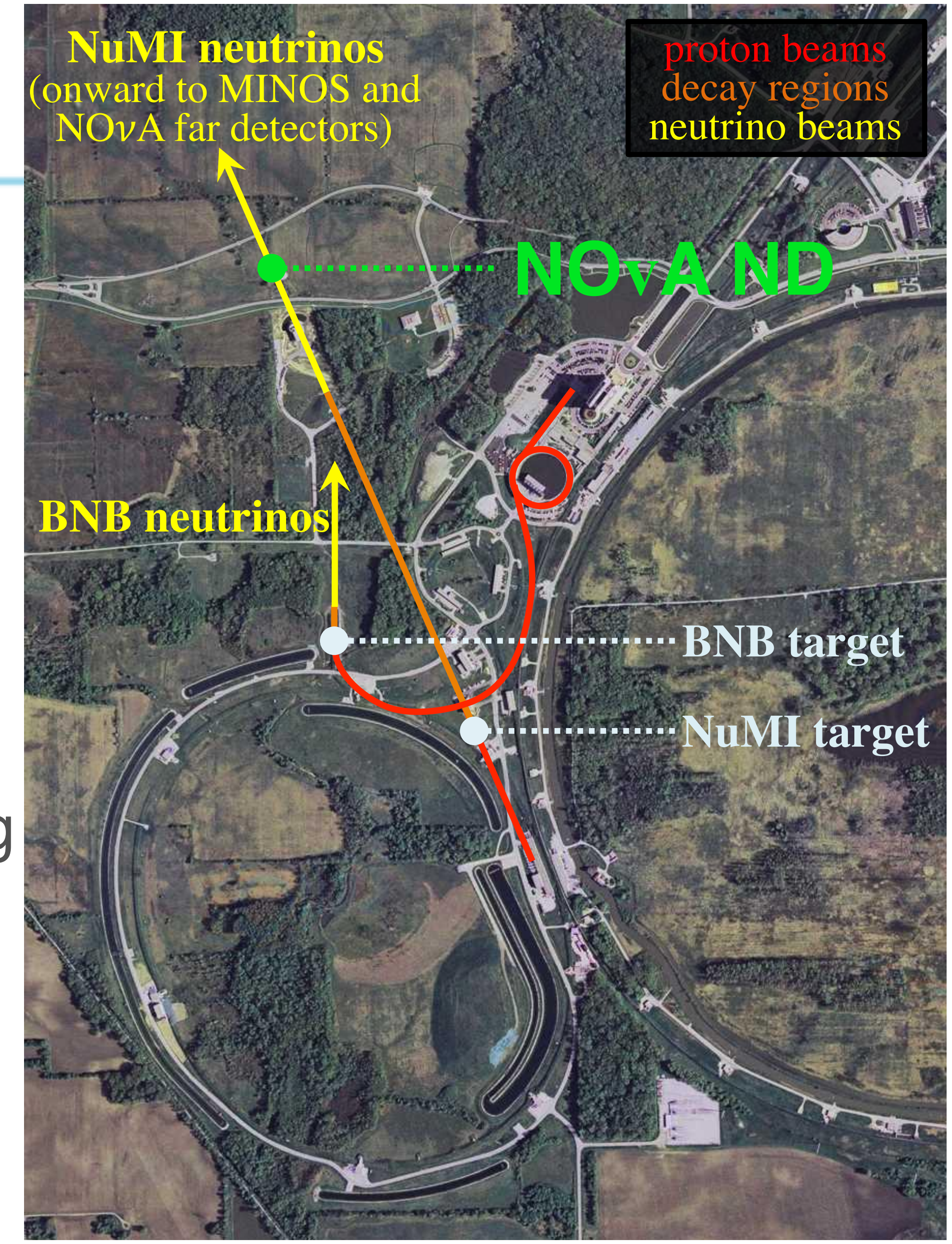

Obrigada!
May Nature continue to be as kind to us as it was when it made this!

BACKUP

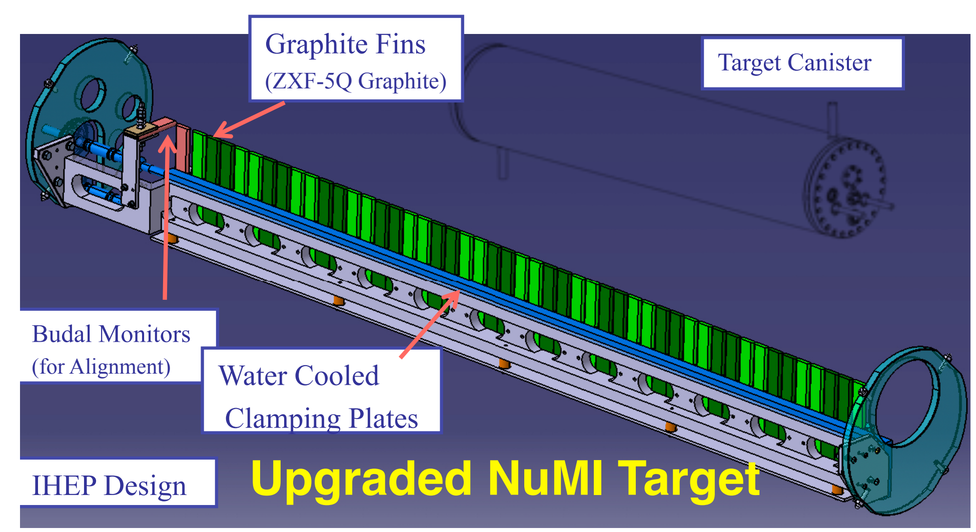
The NuMI Beam



original drawing by R. Zwaska



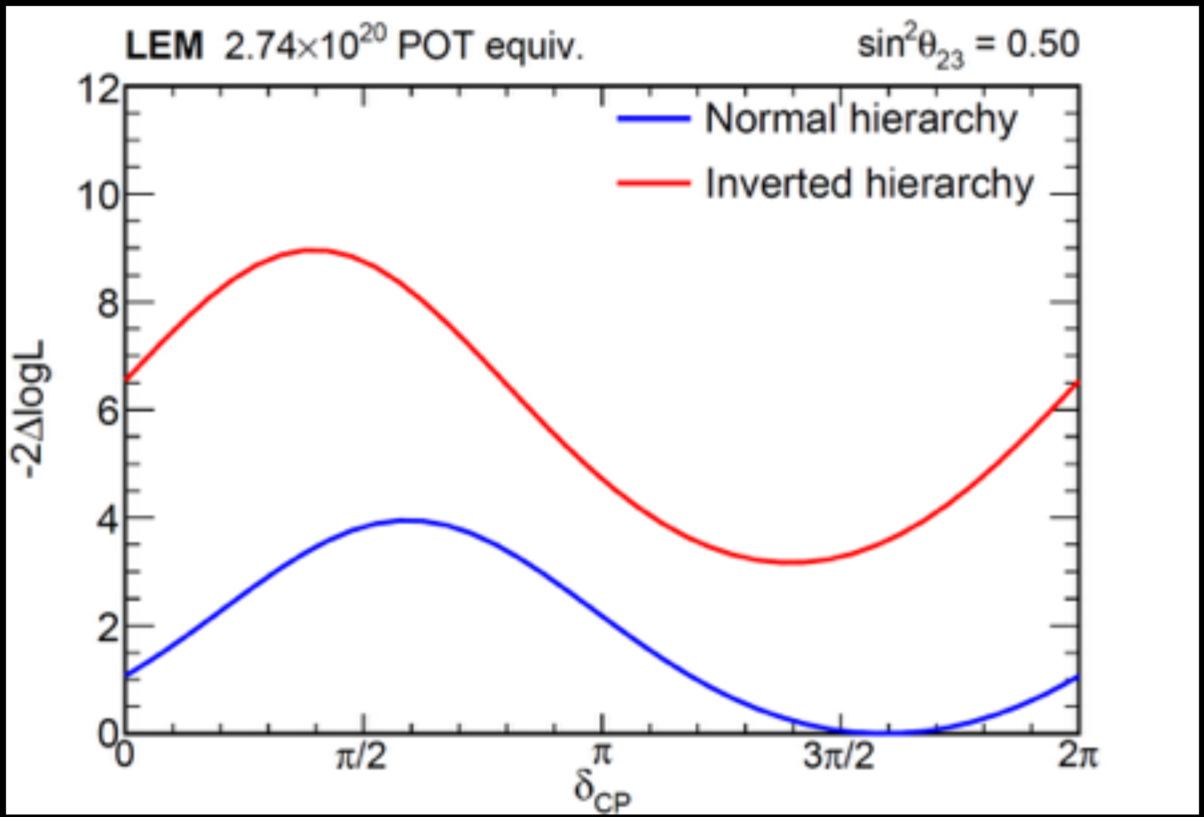
- NuMI upgrades:
  - use Recycler for slip-stacking protons (instead of storing p̄)
  - Main Injector cycle time reduced from 2.2s to 1.33s
    - RF, power supply upgrades
    - New/upgraded kickers and instrumentation
  - upgrades to target station to handle increased power
- Routine 2+6 batches slip-stacking since March 2015
- Record beam power recorded: 521 kW
- Very impressive uptime: 85%
- Progress has been very smooth, all milestones of upgrades have been on time

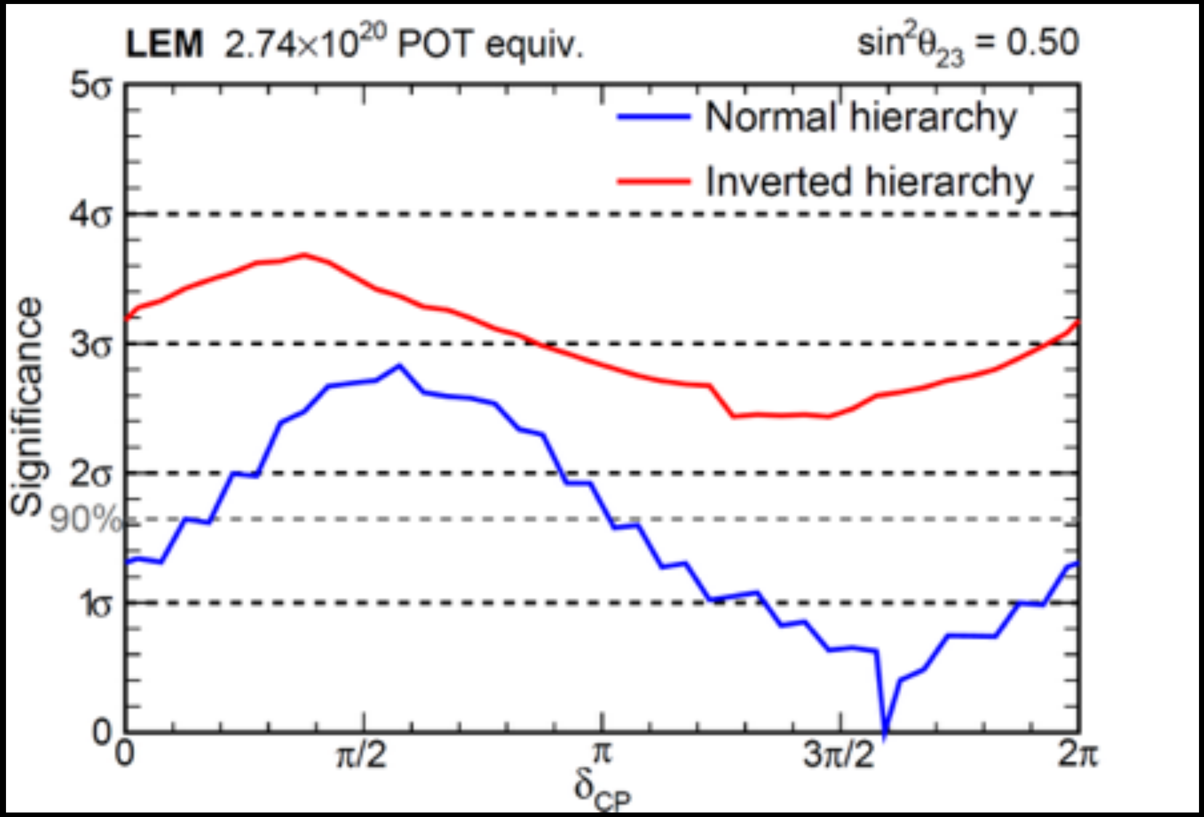


Jon Paley

ELECTRON NEUTRINO APPEARANCE RESULTS

- Taking the reactor measurement of θ_{13} as an input, we can explore compatibility with the mass hierarchy and and δ_{CP} using Feldman-Cousins.
- There is a significant deviation from gaussian limits in this case. Also non-smooth shape due to discreet nature of counting experiment.
- Resulting significances show that at maximal mixing, we disfavor the IH for all δ at >2.2σ with secondary selector. NH for $\delta \in [\,0, \pi\,]$ is mildly disfavored.

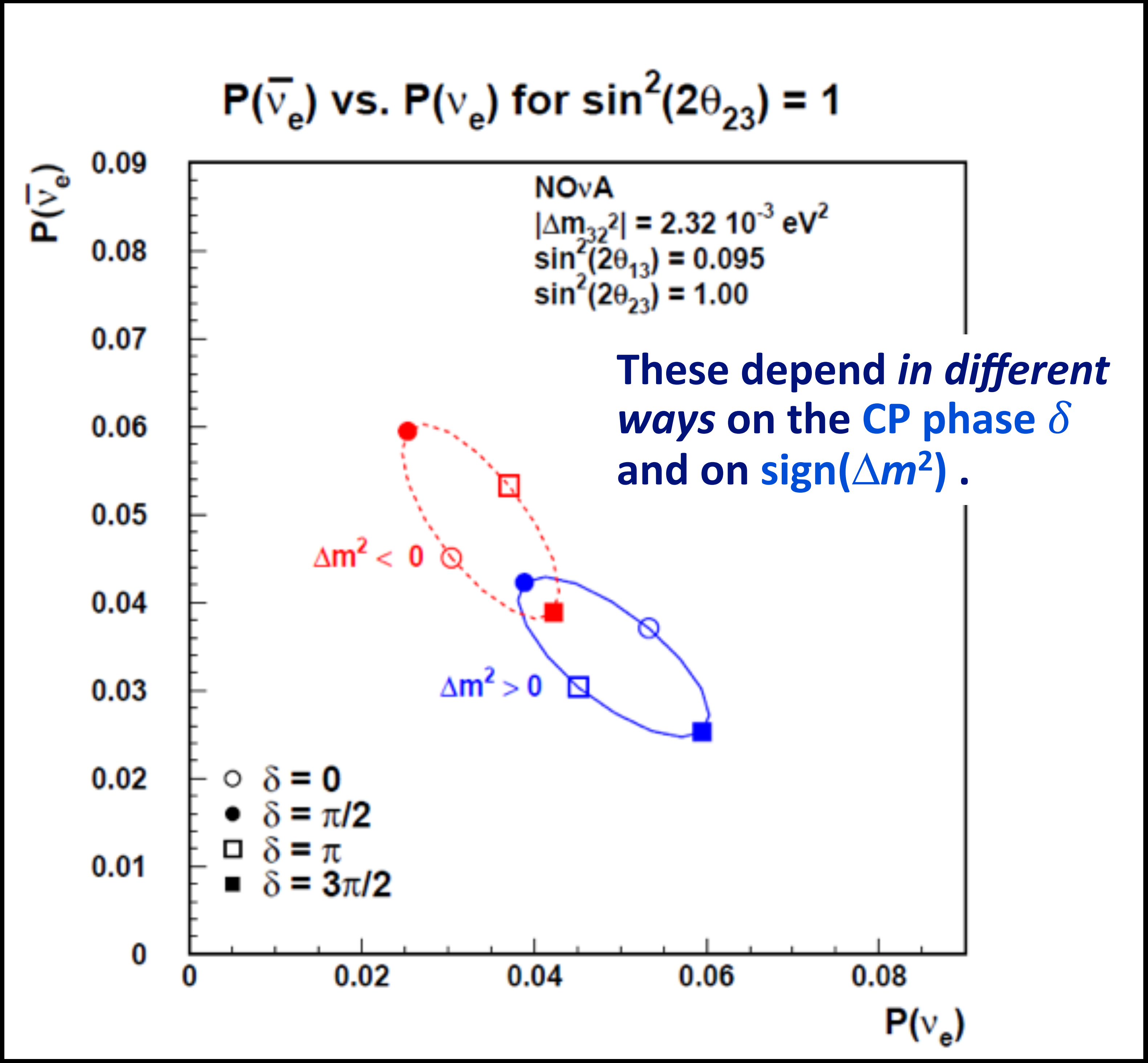




with $\sin^2 2\theta_{13} = 0.086 \pm 0.005$

NOVA PHYSICS

NOνA will measure: $P(\nu_\mu \rightarrow \nu_e)$ **at 2 GeV** *and* $P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e)$ **at 2 GeV**



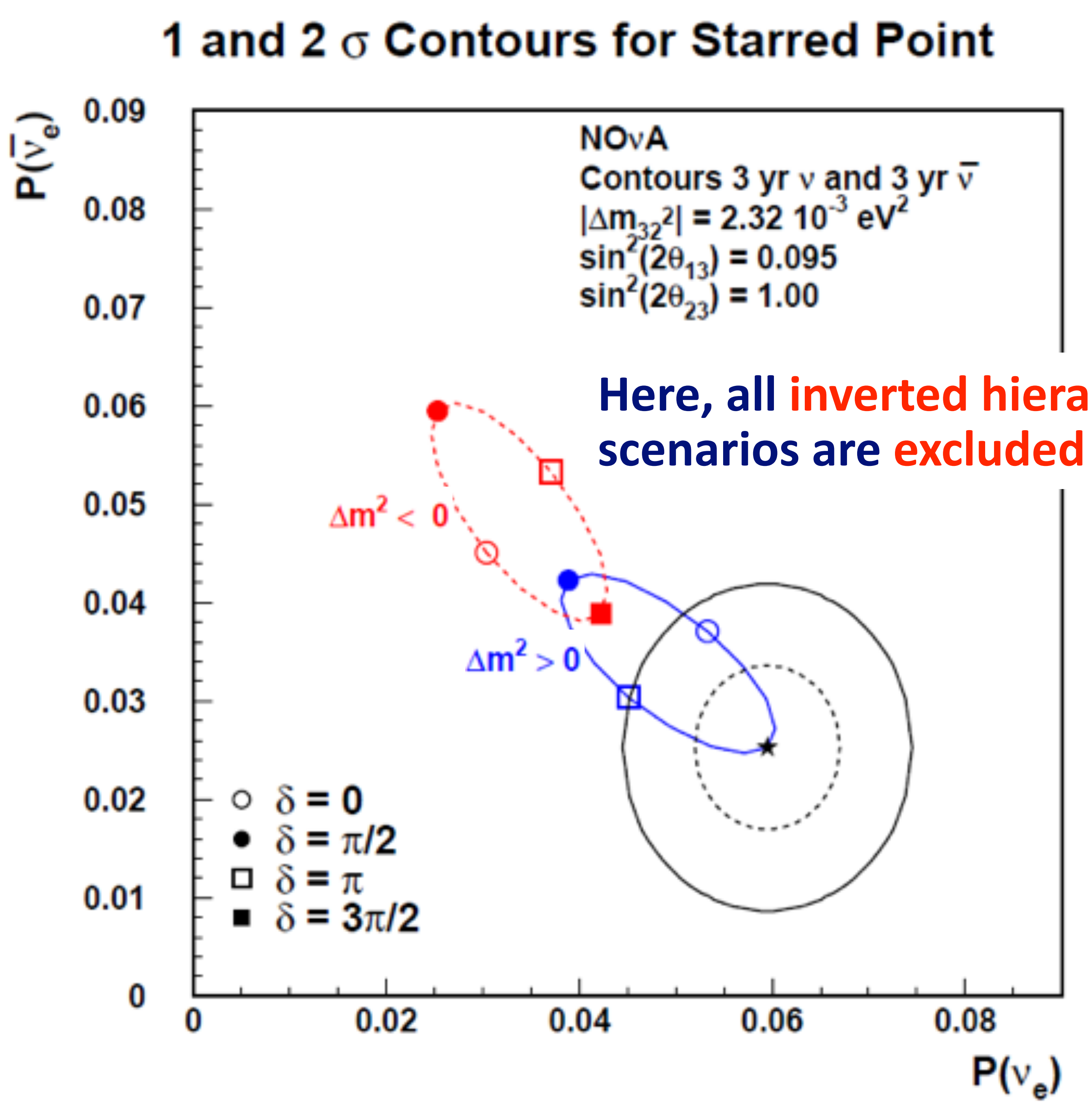
- Large θ_{13} is good news for NOvA. It reduces the overlap between these bi-probability ellipses, reducing the likelihood of degeneracies.

NOVA PHYSICS

Example NOνA result…

Our data will yield allowed regions in $P(\overline{\nu}_e)$ vs. $P(\nu_e)$ space

(3 yr + 3 yr possibility shown)



Here, all inverted hierarchy scenarios are excluded at >2σ.

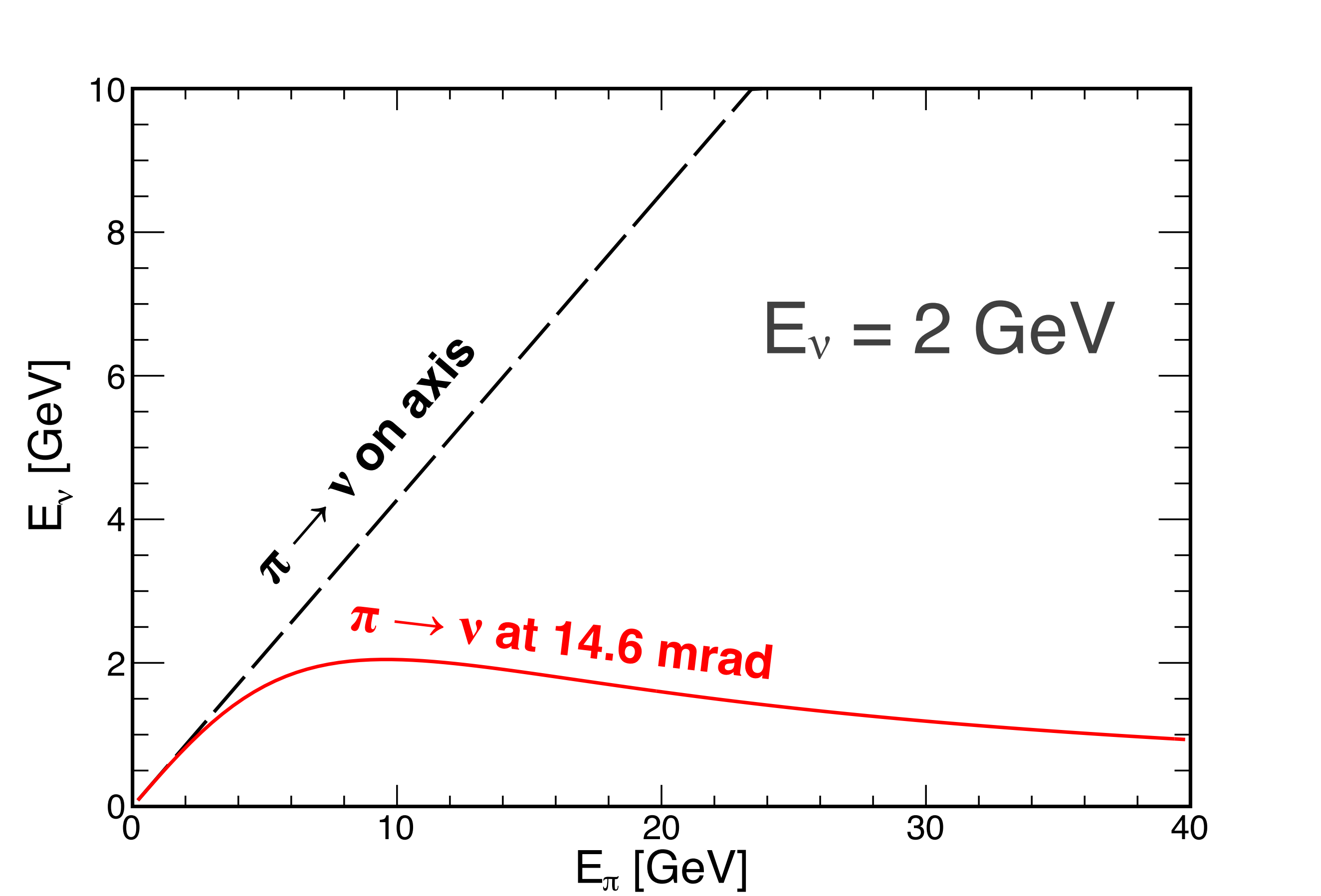
- A measurement of the probabilities might allow resolving the mass hierarchy and provide information on δ_{CP}

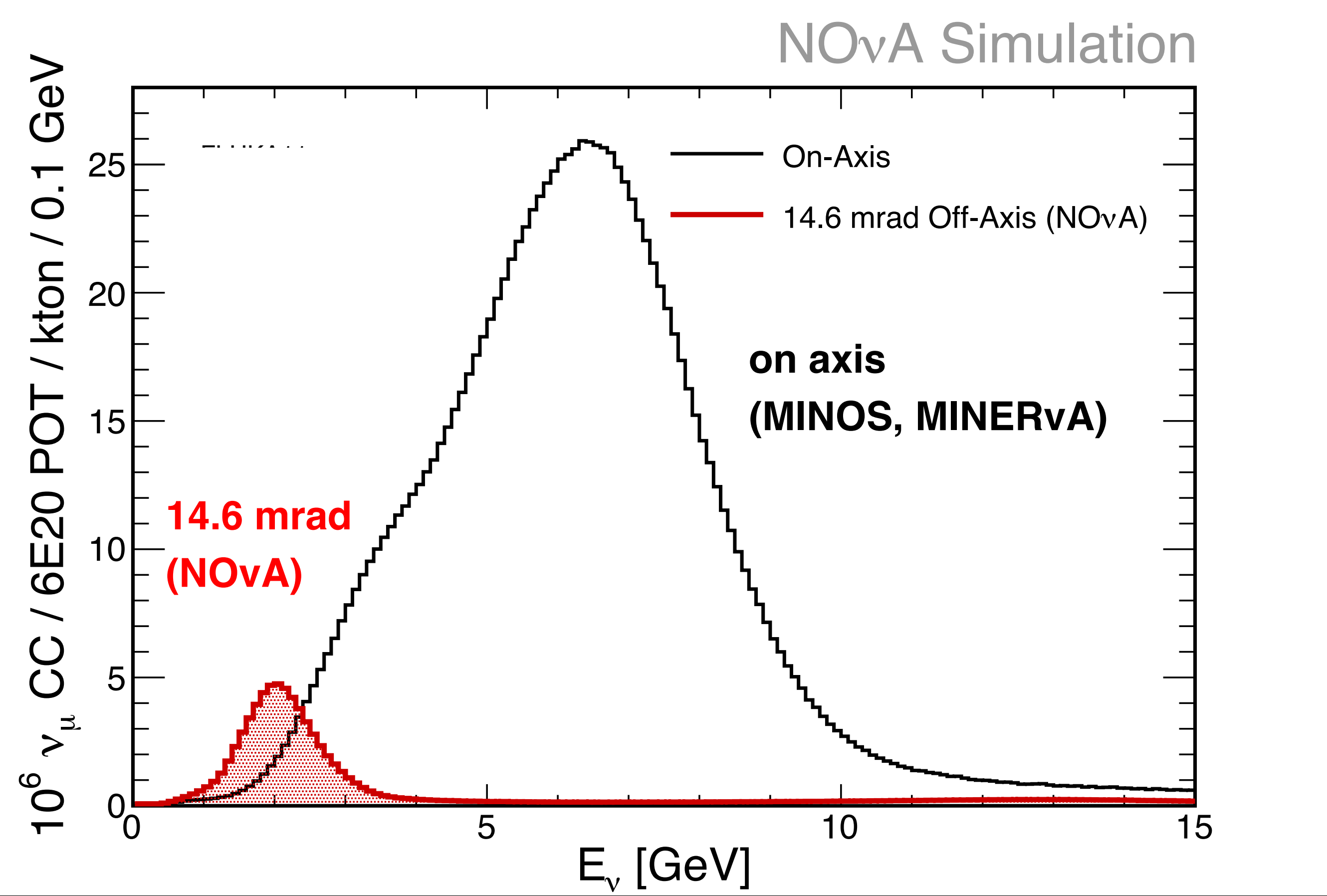
THE OFF-AXIS NUMI BEAM

- NOνA detectors are located 14 mrad off the NuMI beam axis.
- With the medium-energy NuMI configuration, it yields a narrow 2-GeV spectrum at the NOνA detectors due to meson decay kinematics:

$$E_\nu = \frac{1-(m_\mu/m_\pi)^2}{1+\gamma^2\tan^2\theta}E_\pi$$

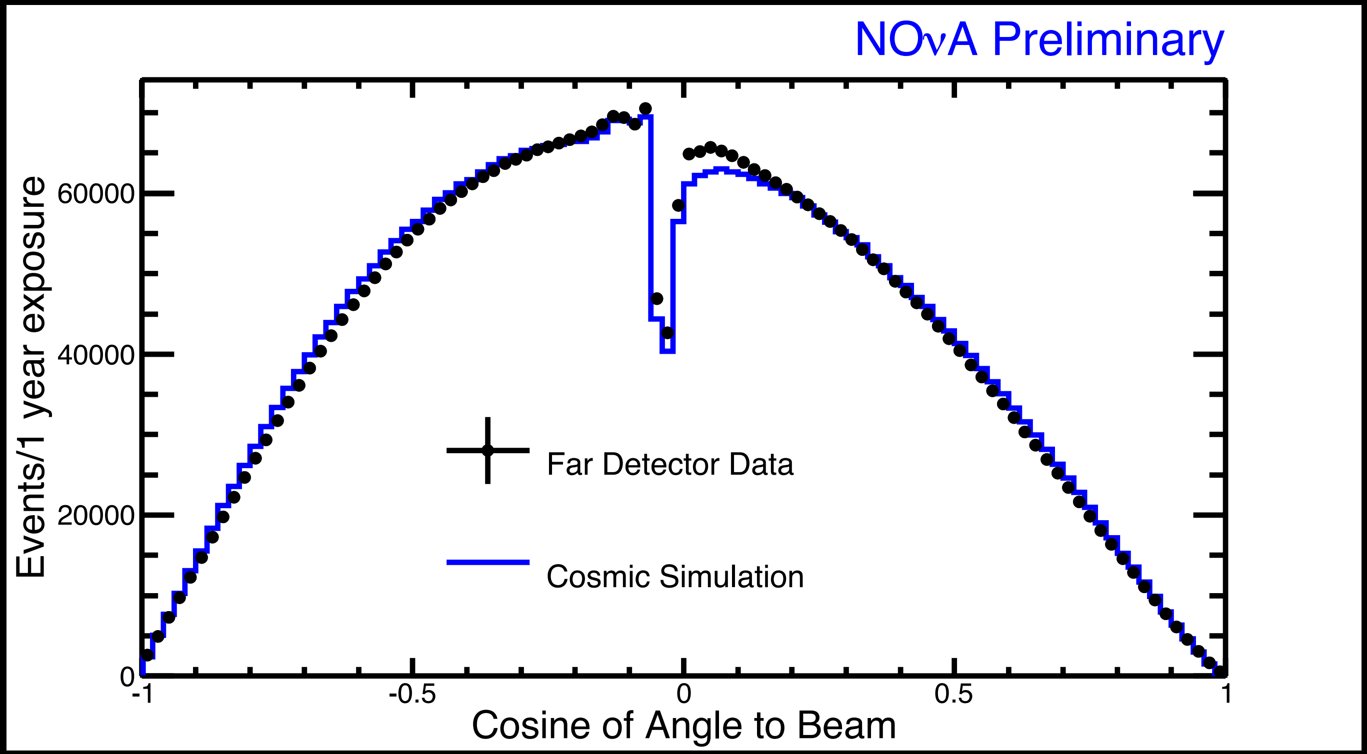
- Location reduces NC and νe CC backgrounds in the oscillation analyses while maintaining high ν_μ flux at 2 GeV.

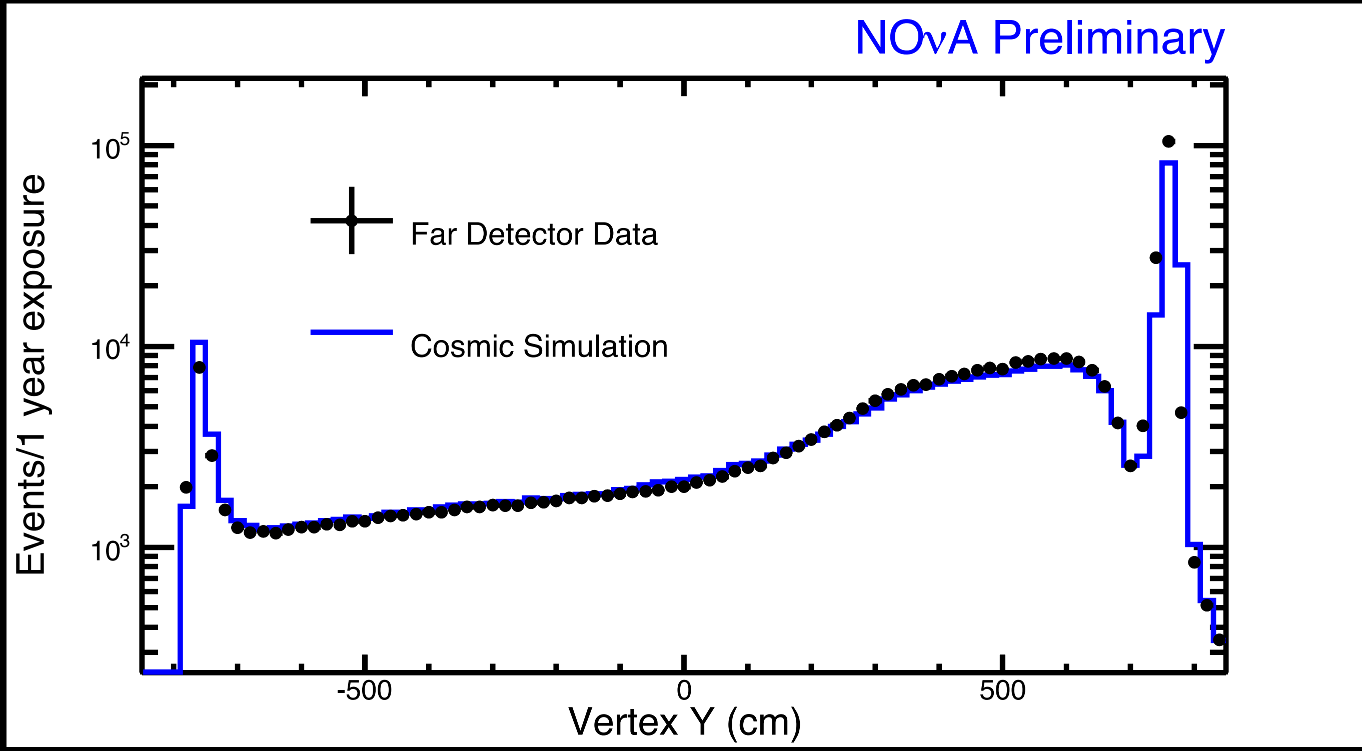




COSMIC BACKGROUND DATA

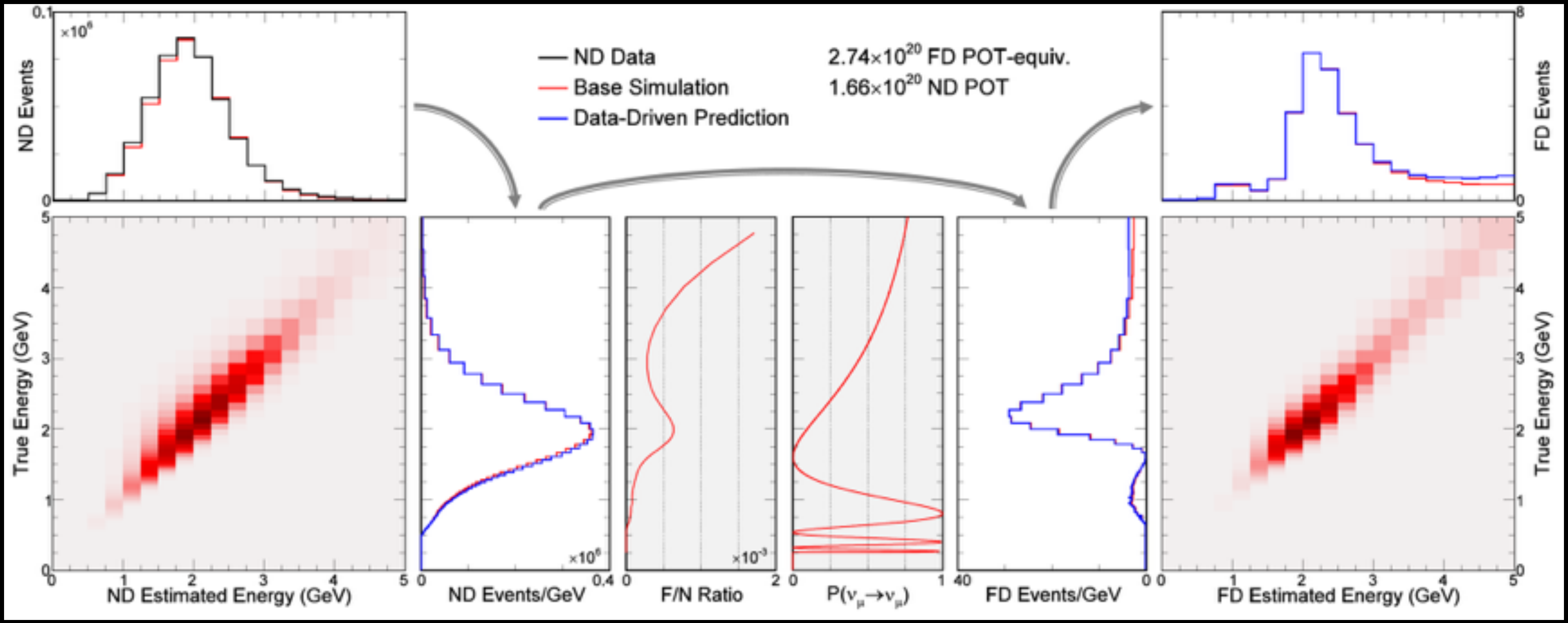
- We take data independent of the beam spills for calibration and cosmic background studies.
- These data is well described by CRY simulation.



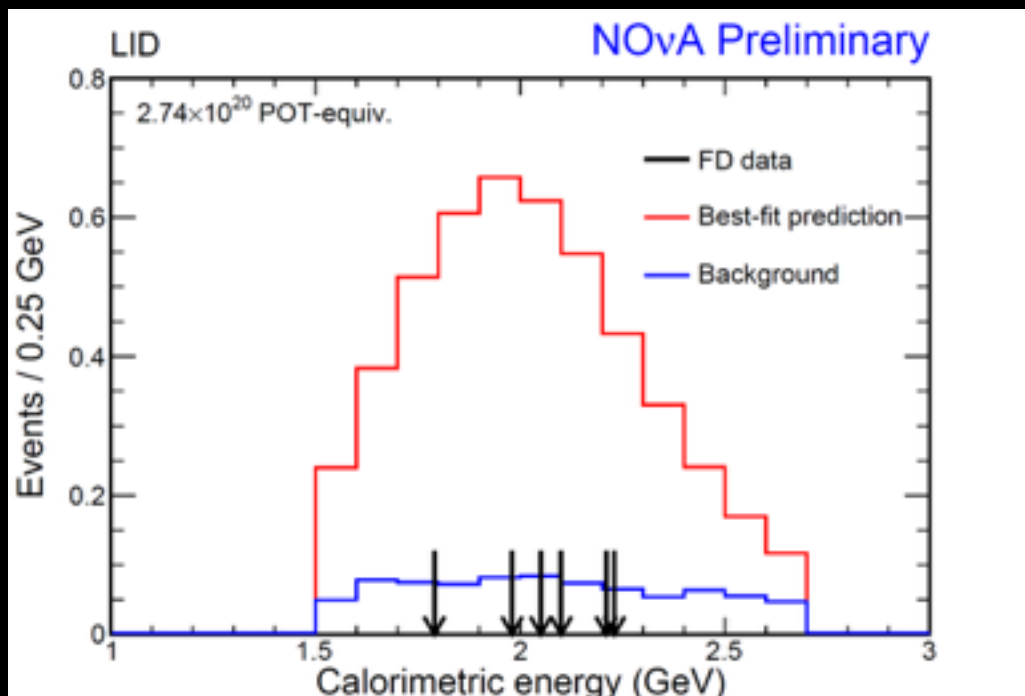


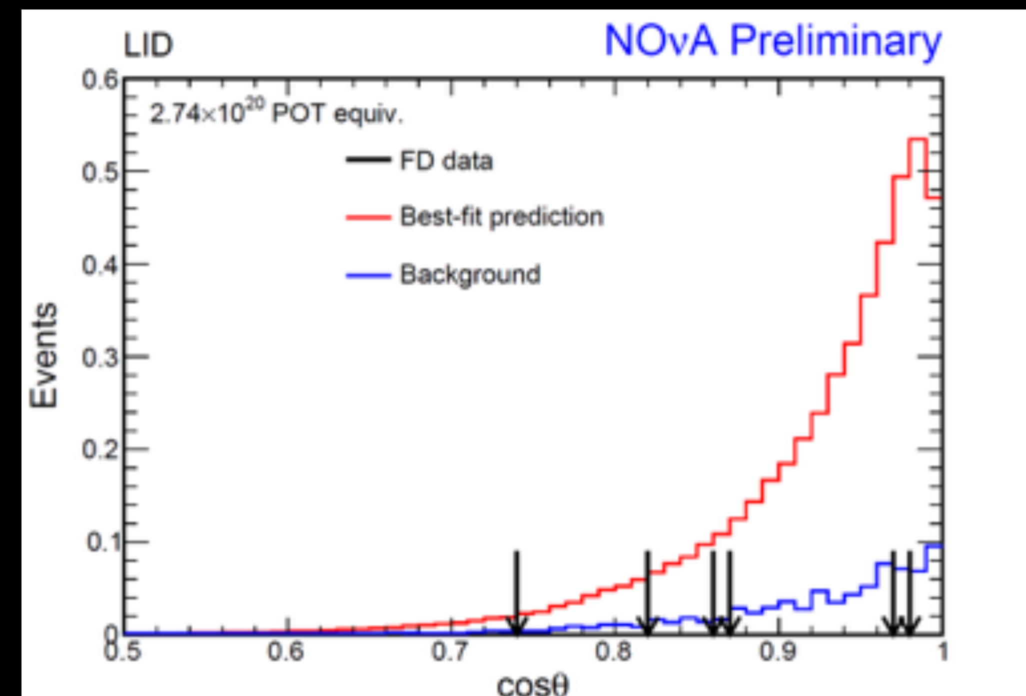
DATA-DRIVEN FAR DETECTOR MUON NEUTRINO PREDICTION

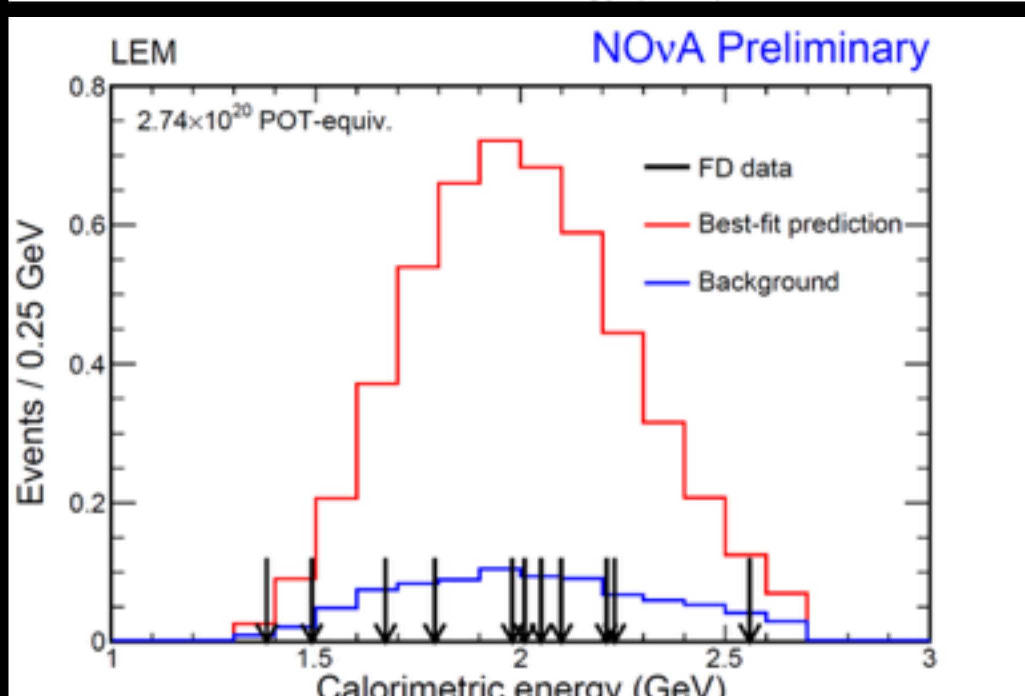
- Estimate the underlying true energy distribution of selected ND events.
- Multiply by expected Far/Near event ratio and $\nu_\mu \rightarrow \nu_\mu$ oscillation probability as a function of true energy.
- Convert FD true energy distribution into predicted FD reconstructed energy distribution.
- Systematic uncertainties assessed by varying all MC-based steps.

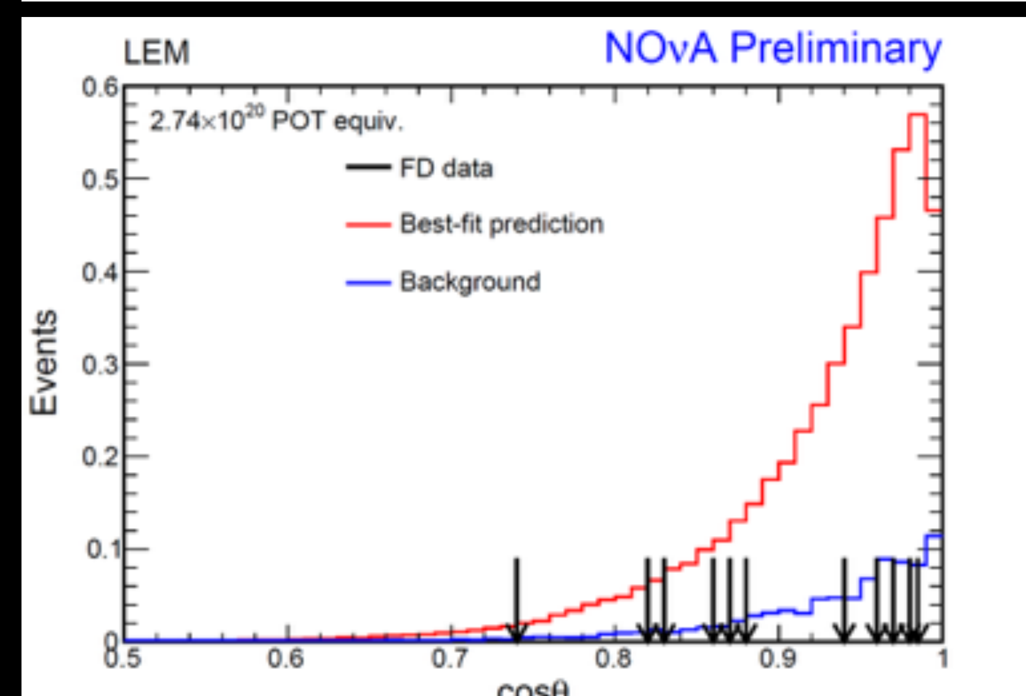


ENERGY AND ANGULAR DISTRIBUTIONS OF ELECTRON NEUTRINO CANDIDATES



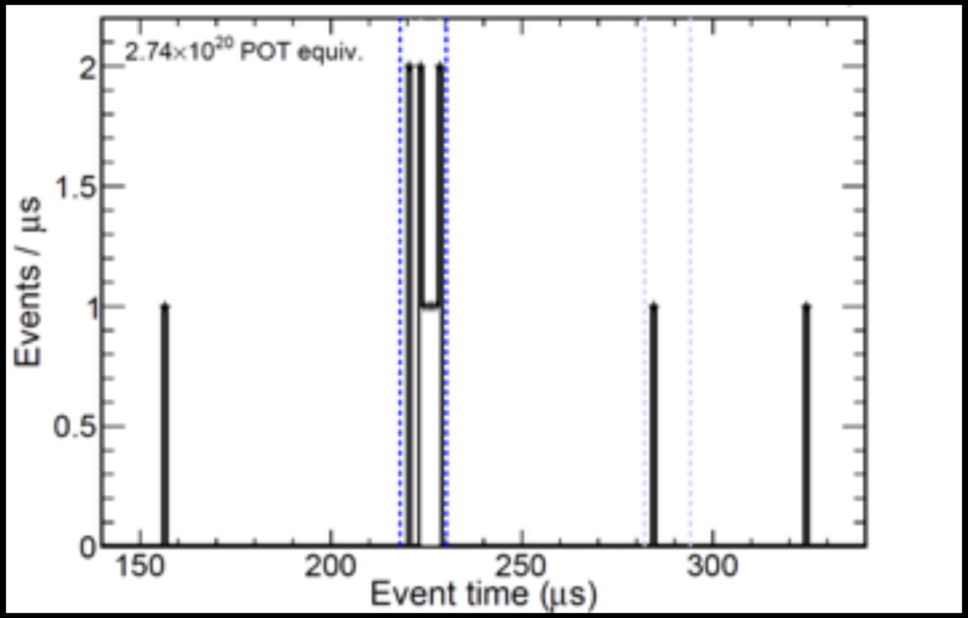


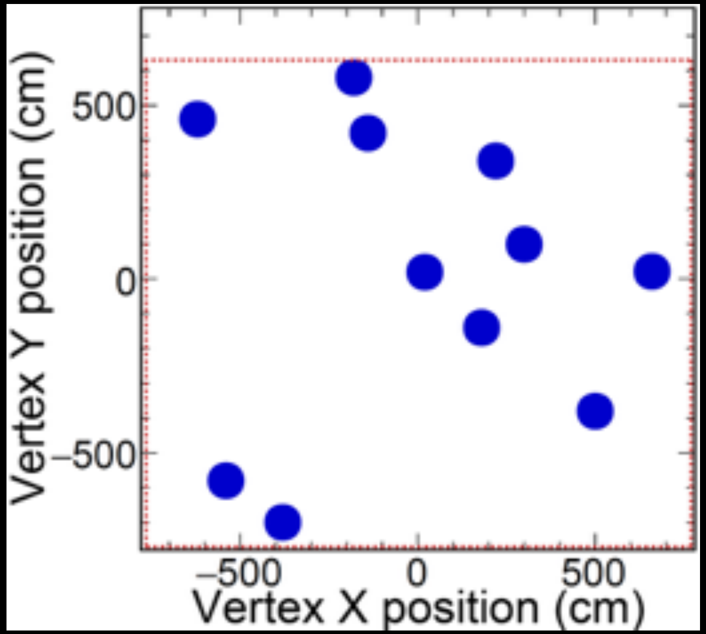


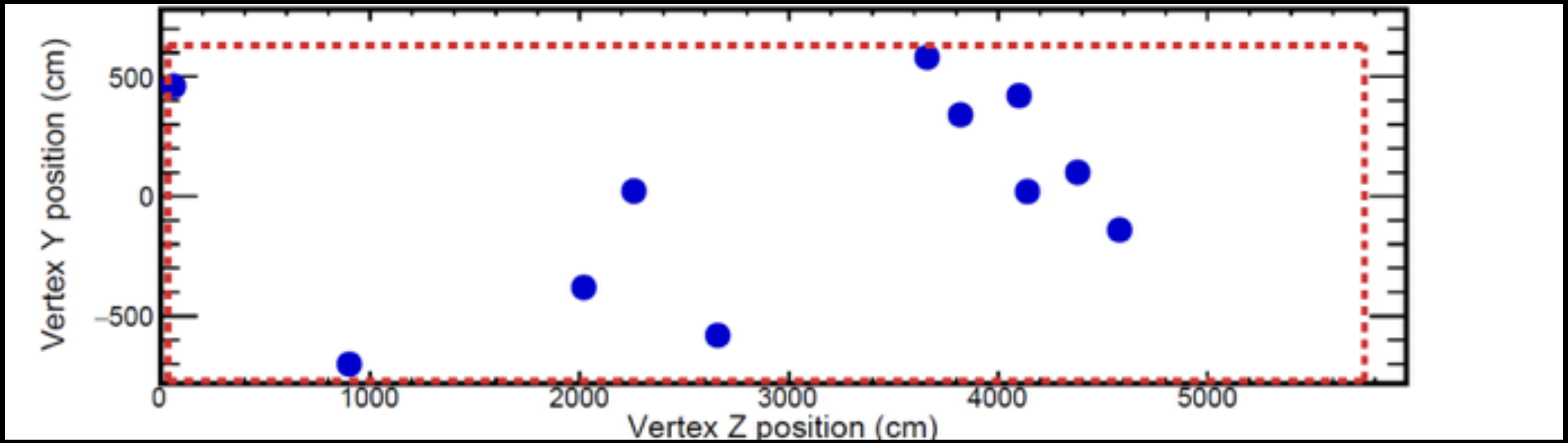


ALL 11 EVENTS ARE REASONABLY DISTRIBUTED IN ENERGY AND ANGLE

TIMING AND VERTEX POSITION DISTRIBUTIONS OF ELECTRON NEUTRINO CANDIDATES

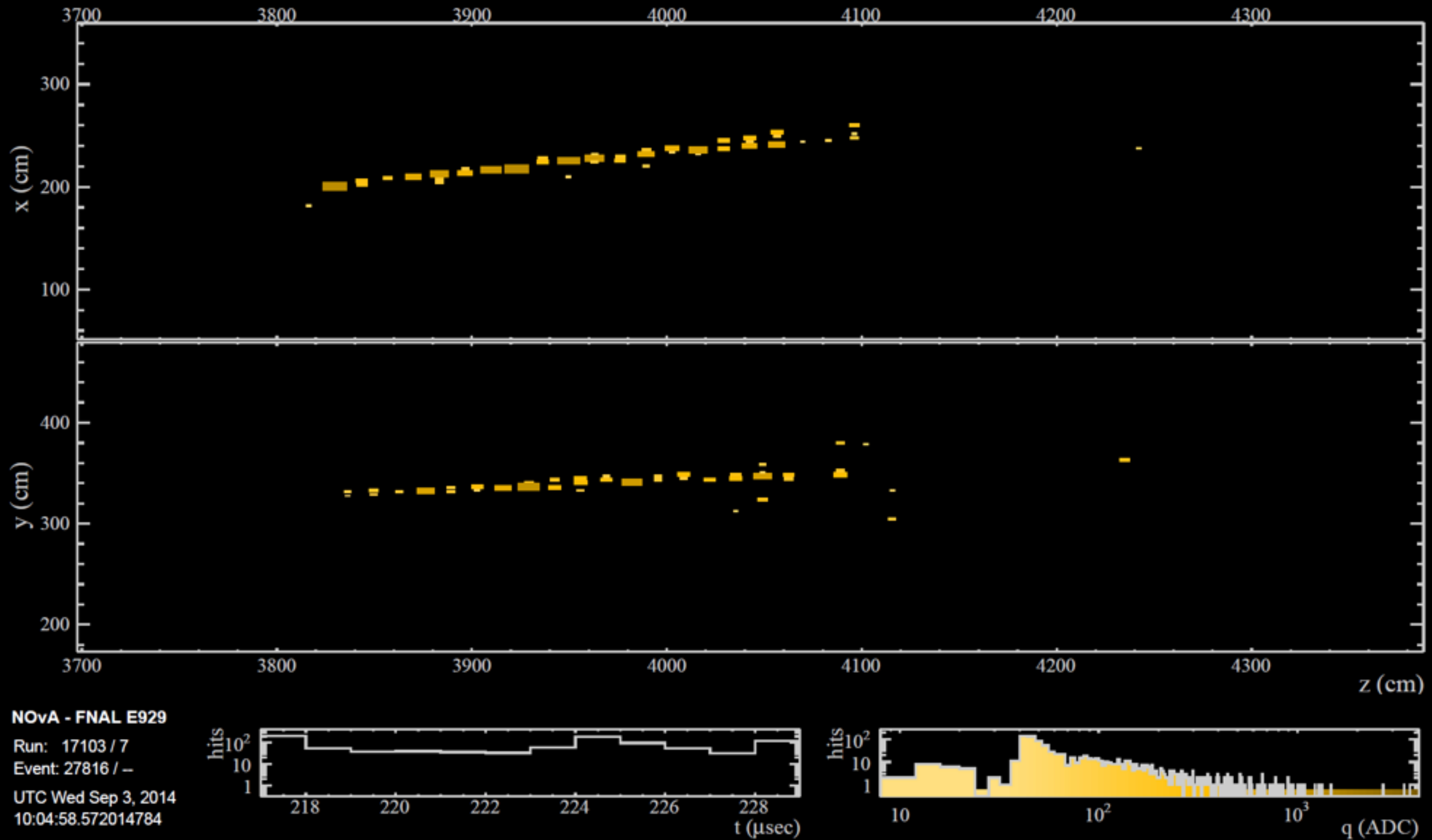


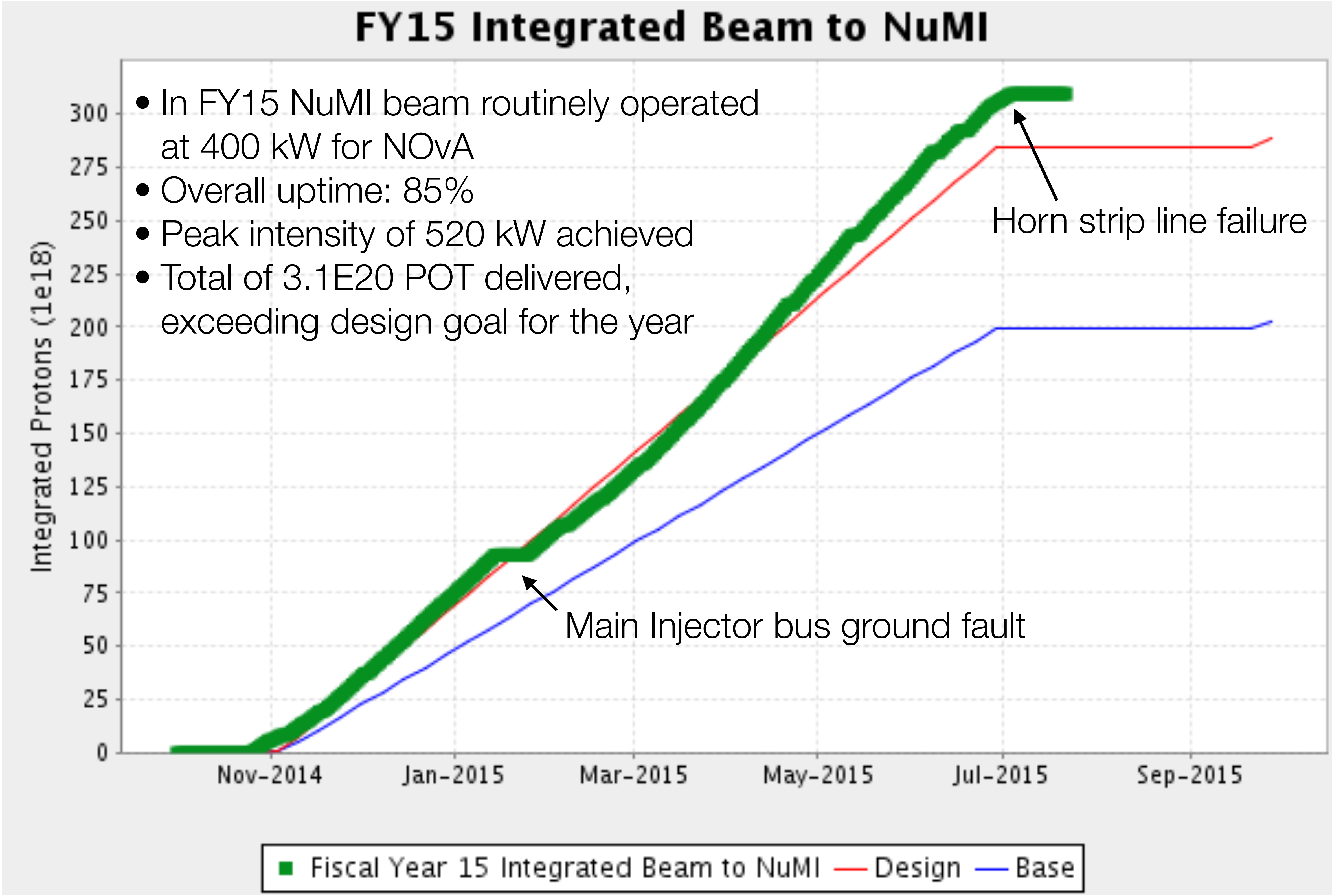




ALL 11 EVENTS ARE REASONABLY DISTRIBUTED IN TIME AND SPACE

ELECTRON NEUTRINO CANDIDATE

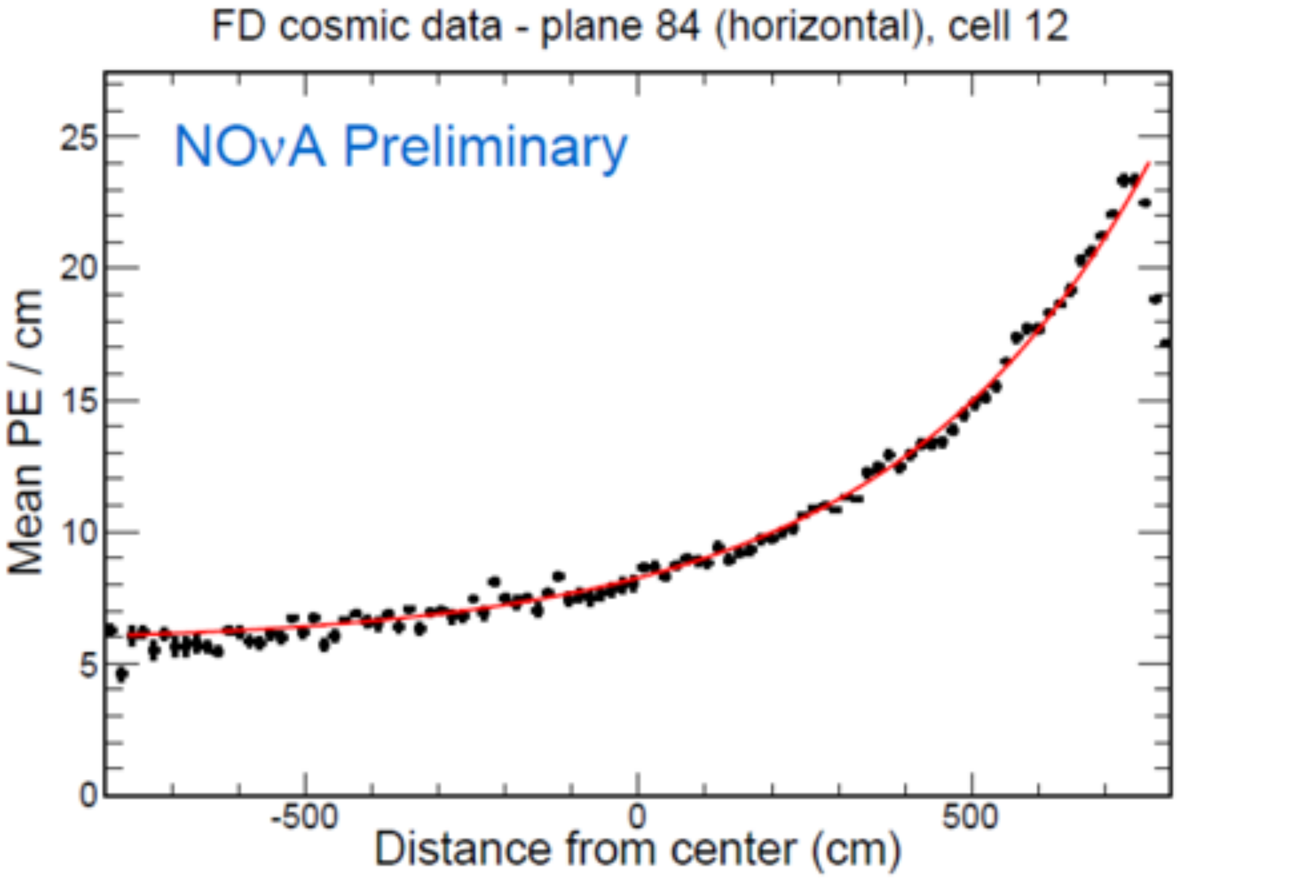


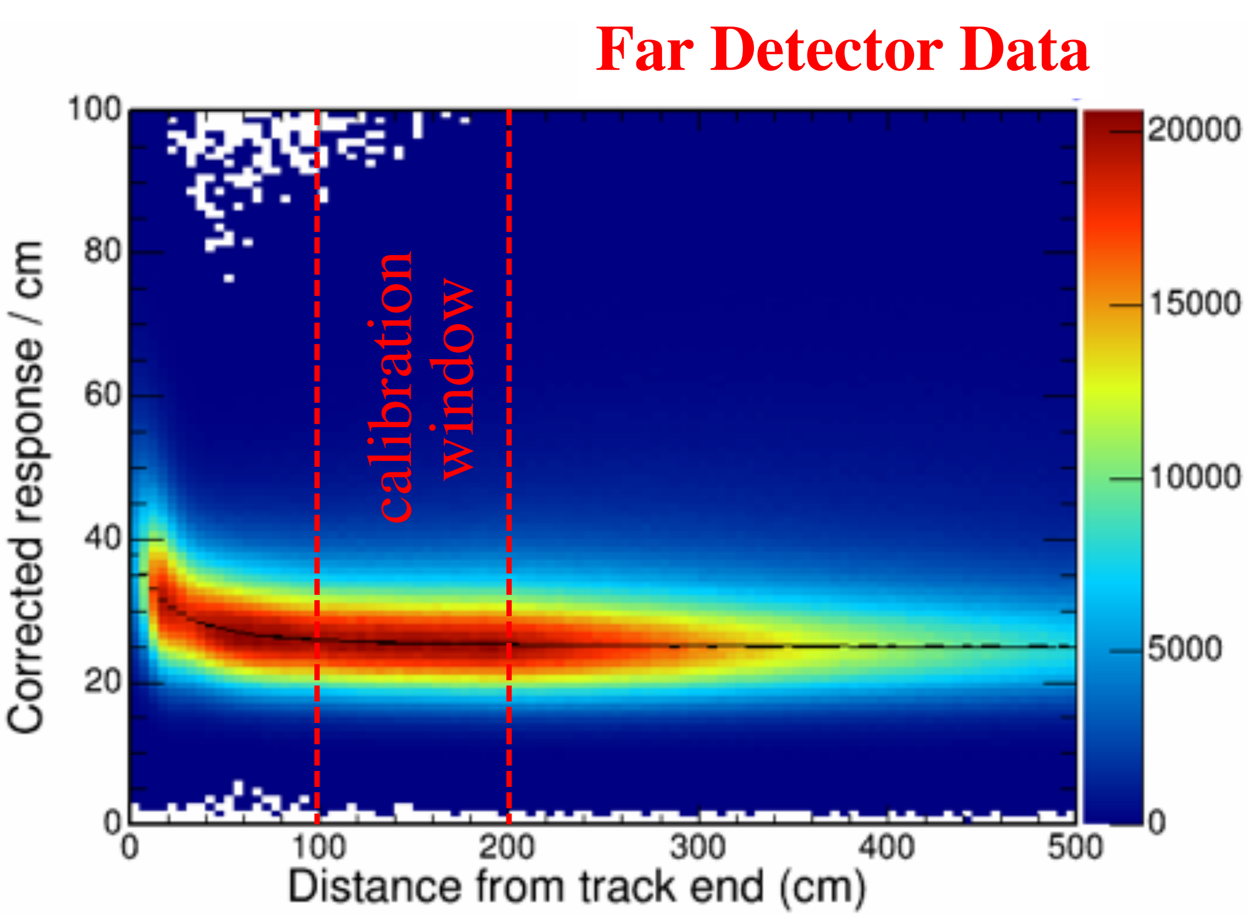


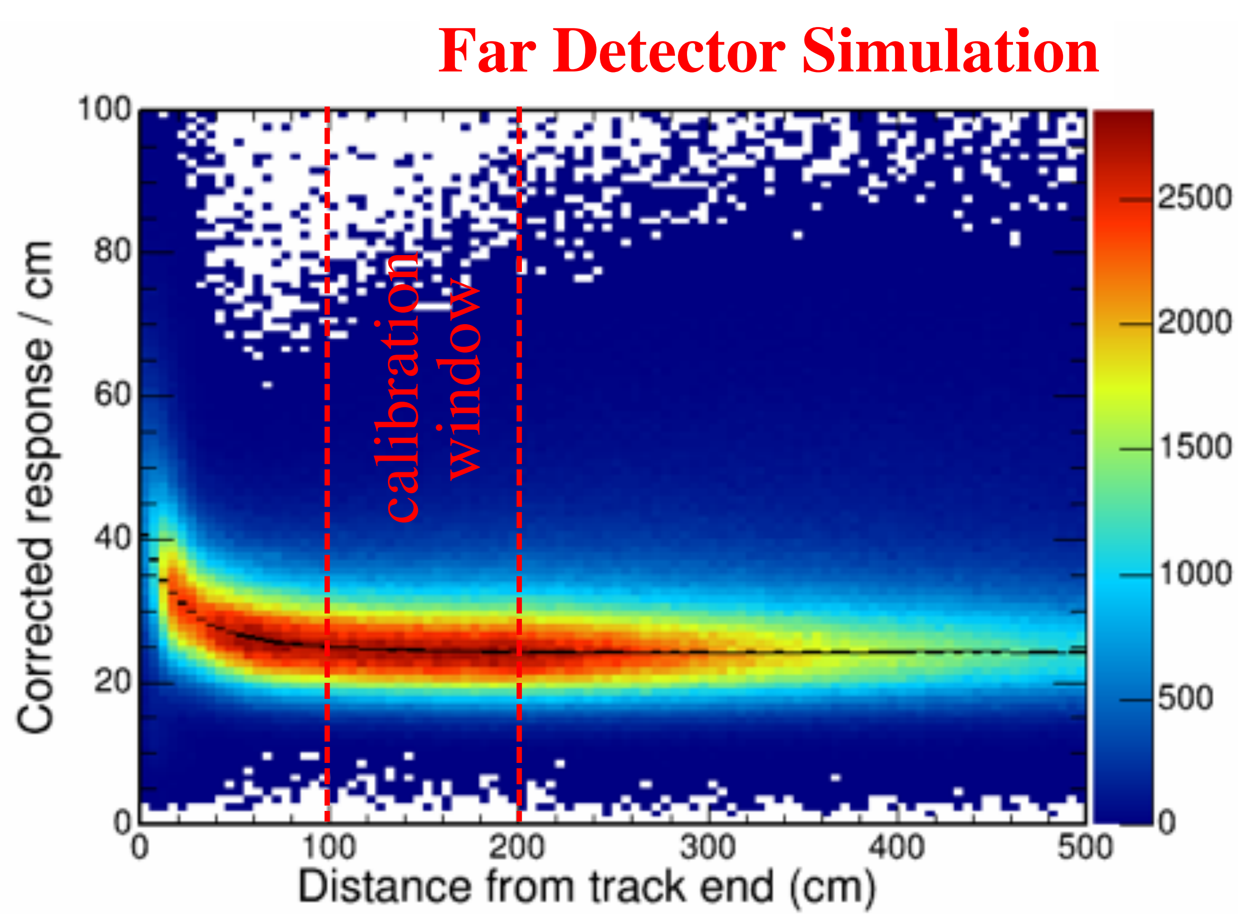
US FY2015 NuMI Beam Performance

Calibration

- **Biggest effect** that needs correction is **attenuation** in the WLS fiber
  Example FD cell ⟶
- **Stopping muons** provide a standard candle for setting absolute energy scale *(below)*





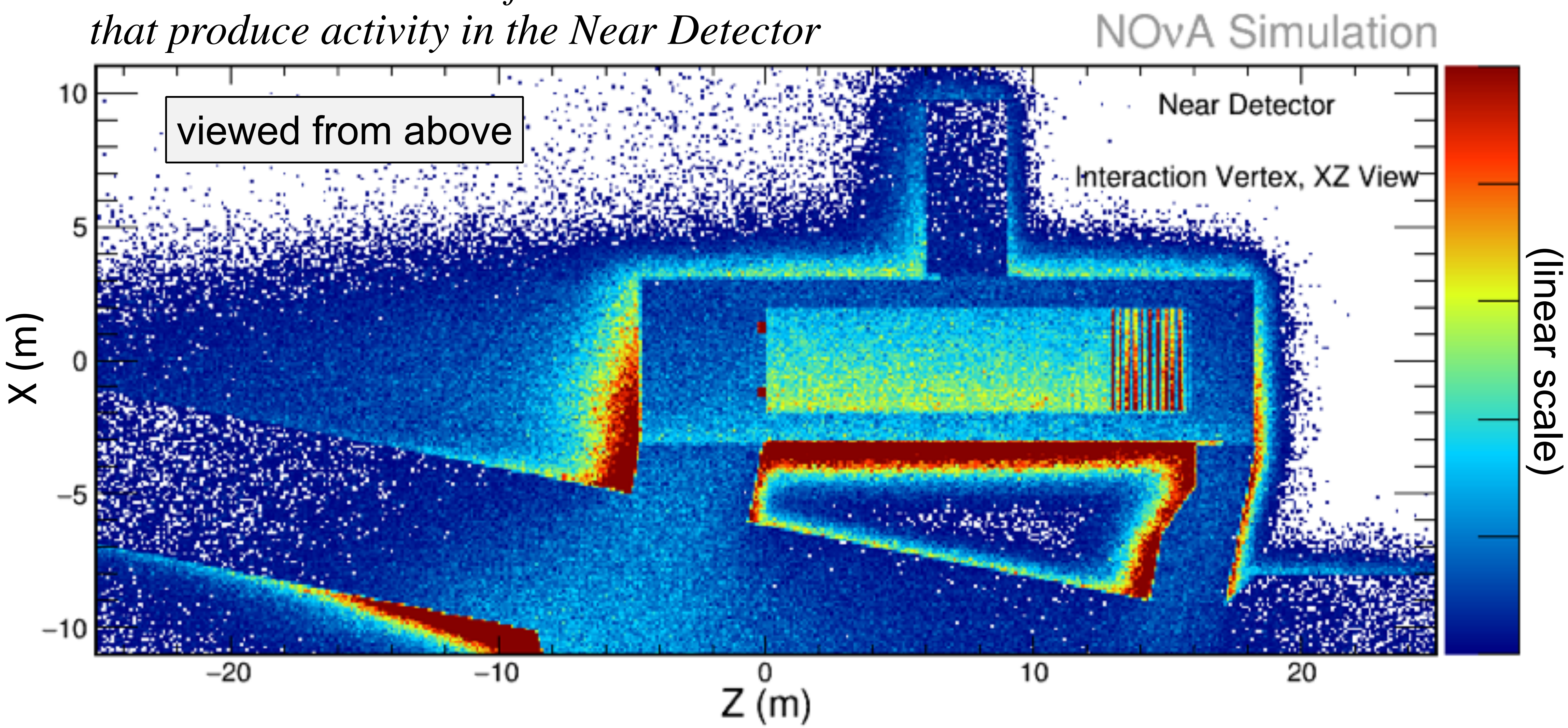


Simulation

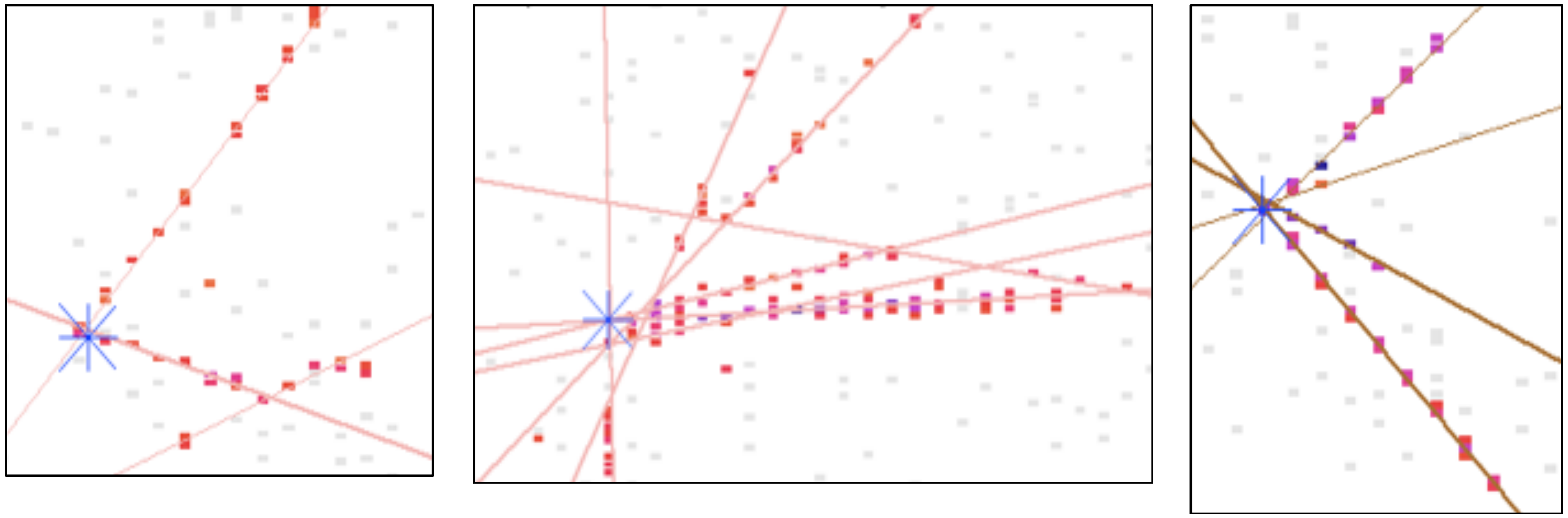
Highly detailed end-to-end simulation chain

- Beam hadron production, propagation; neutrino flux: **FLUKA/FLUGG**
- Cosmic ray flux: **CRY**
- Neutrino interactions and FSI modeling: **GENIE**
- Detector simulation: **GEANT4**
- Readout electronics and DAQ: **Custom simulation routines**

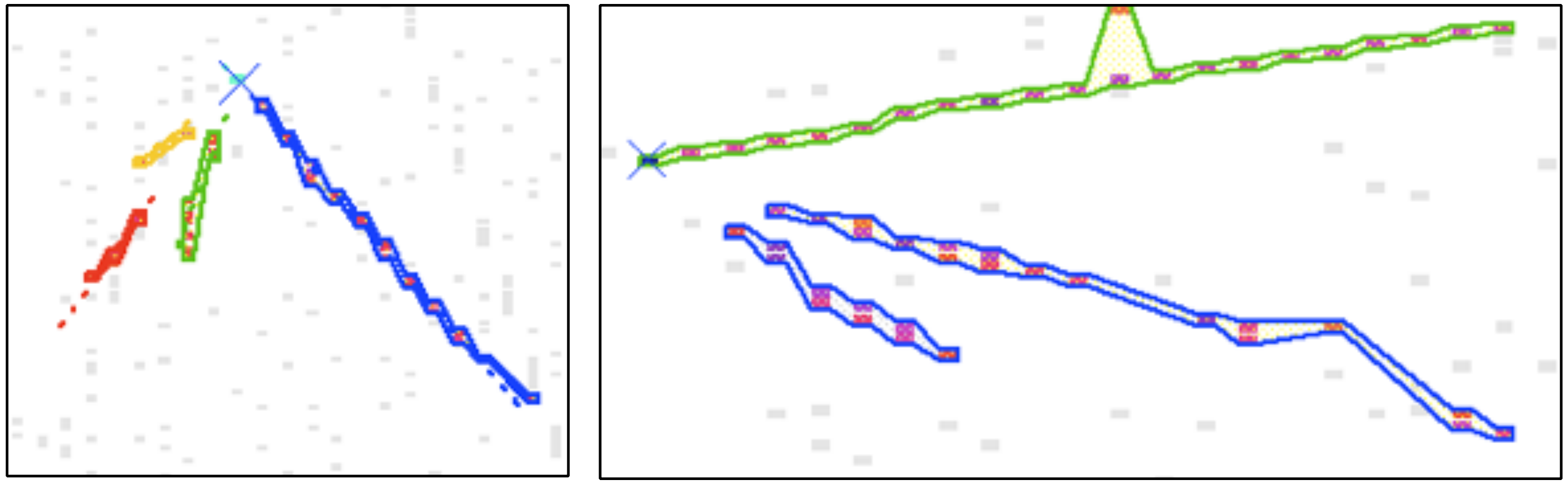
Simulation: Locations of neutrino interactions that produce activity in the Near Detector



Reconstruction

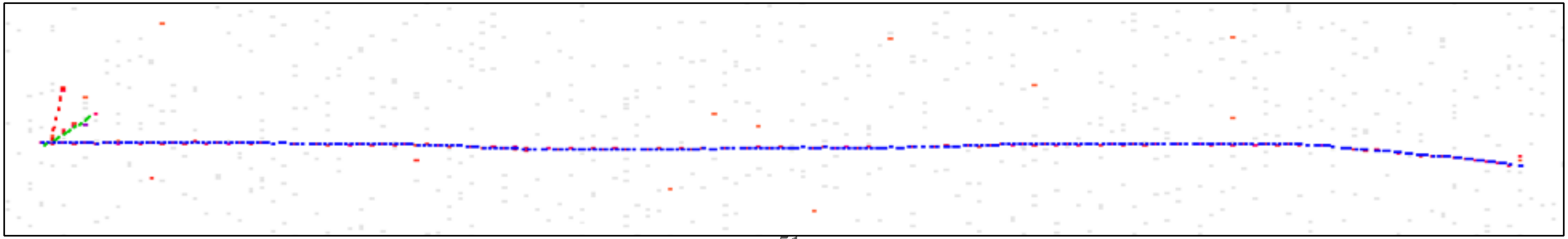


Vertexing: Find **lines of energy depositions** w/ Hough transform
CC events: 11 cm resolution

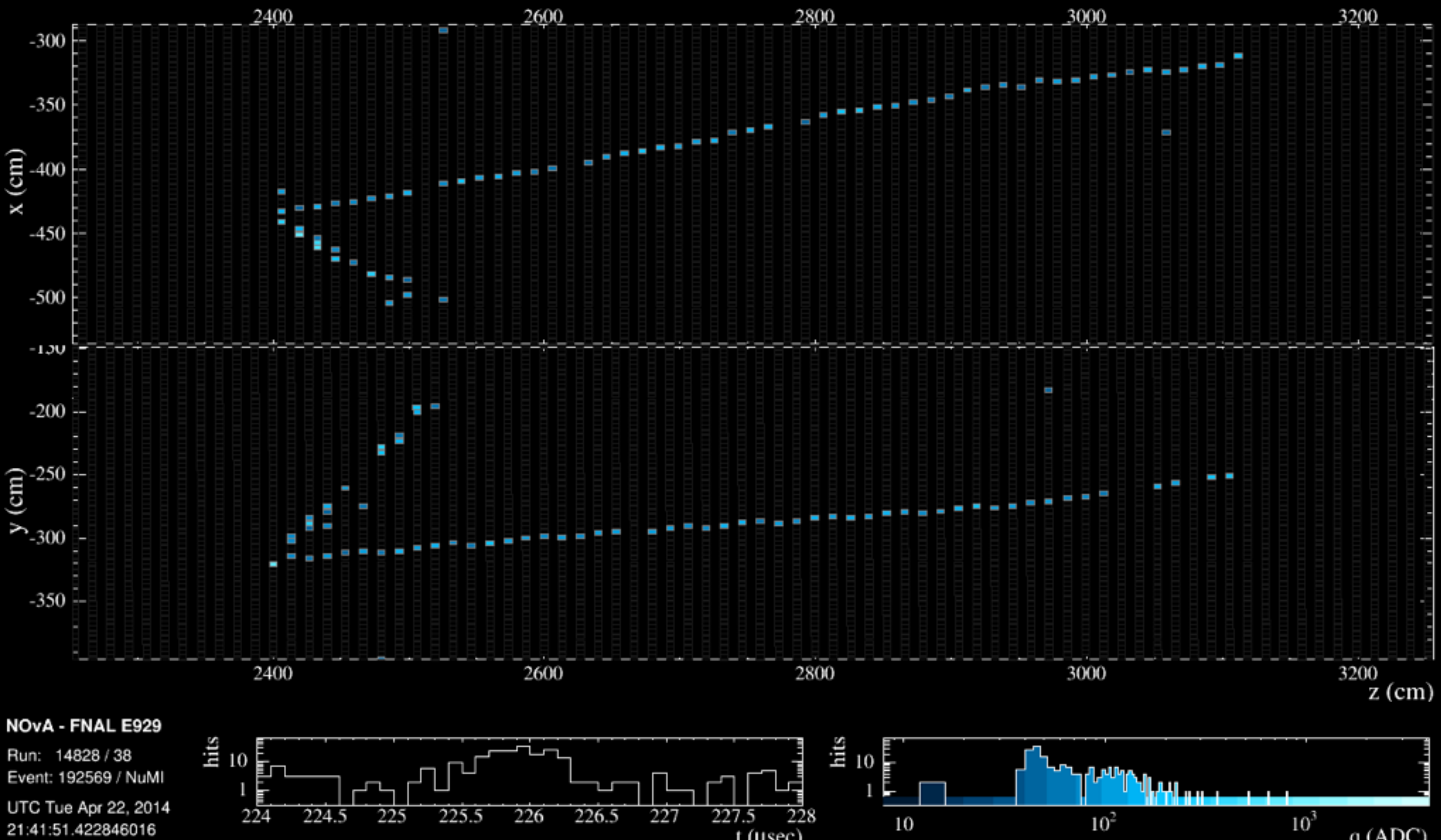


Clustering: Find **clusters in angular space** around vertex. **Merge views** via topology and prong *dE*/*dx*

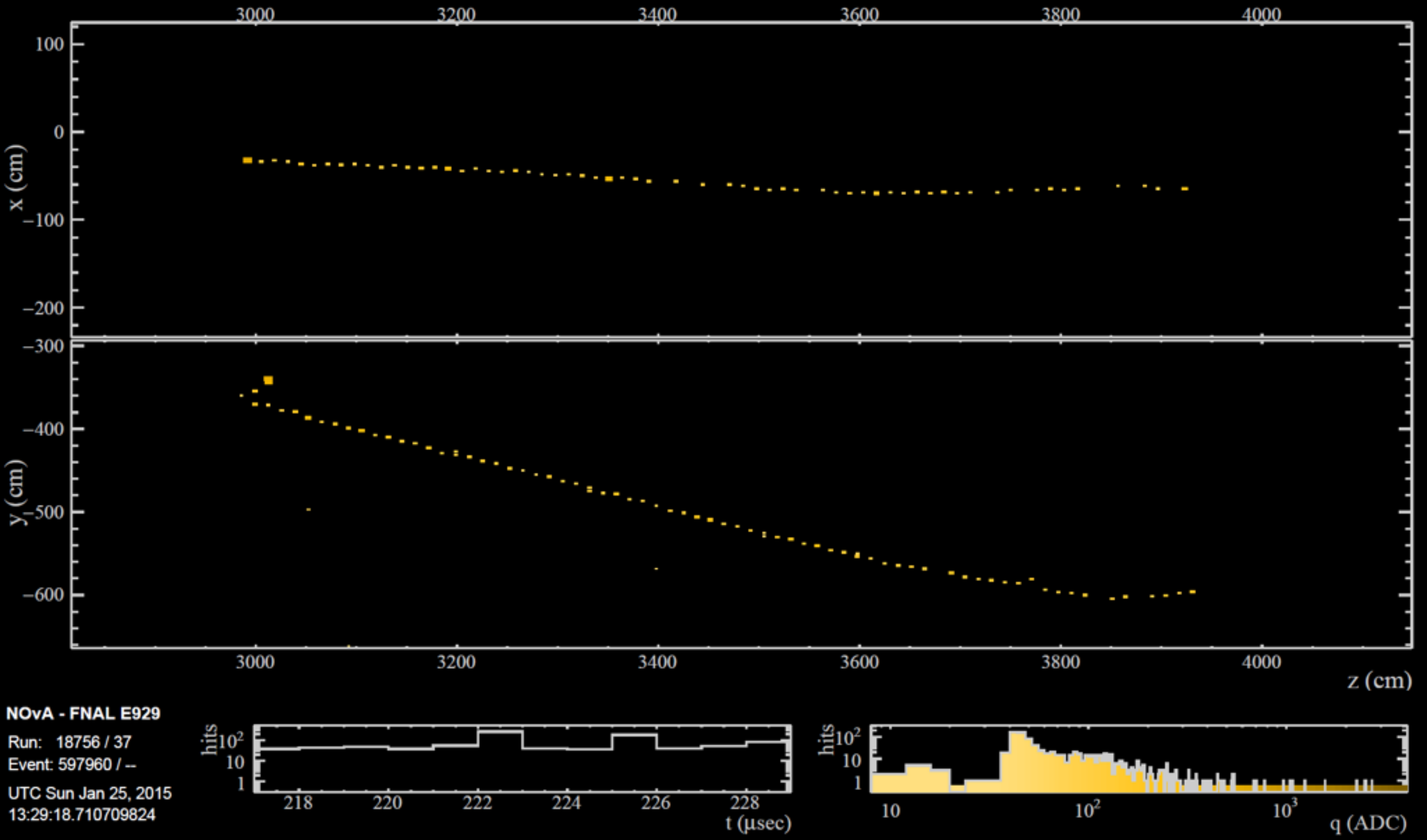
Tracking: Trace particle trajectories with **Kalman filter** tracker (below). Also have a **cosmic ray tracker**: lightweight, very fast, and useful for large calibration samples and online monitoring tools.



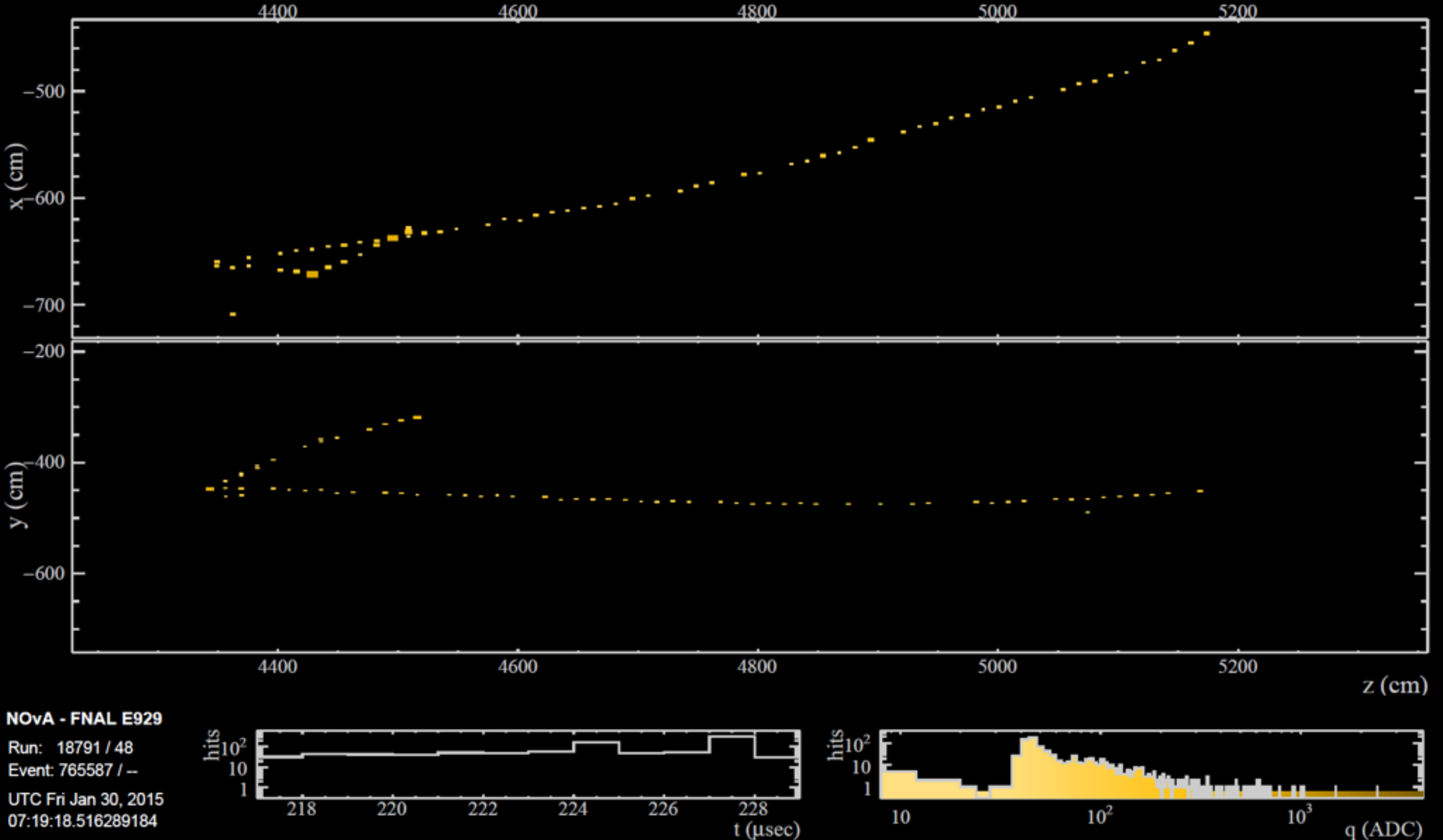
MUON NEUTRINO CANDIDATE



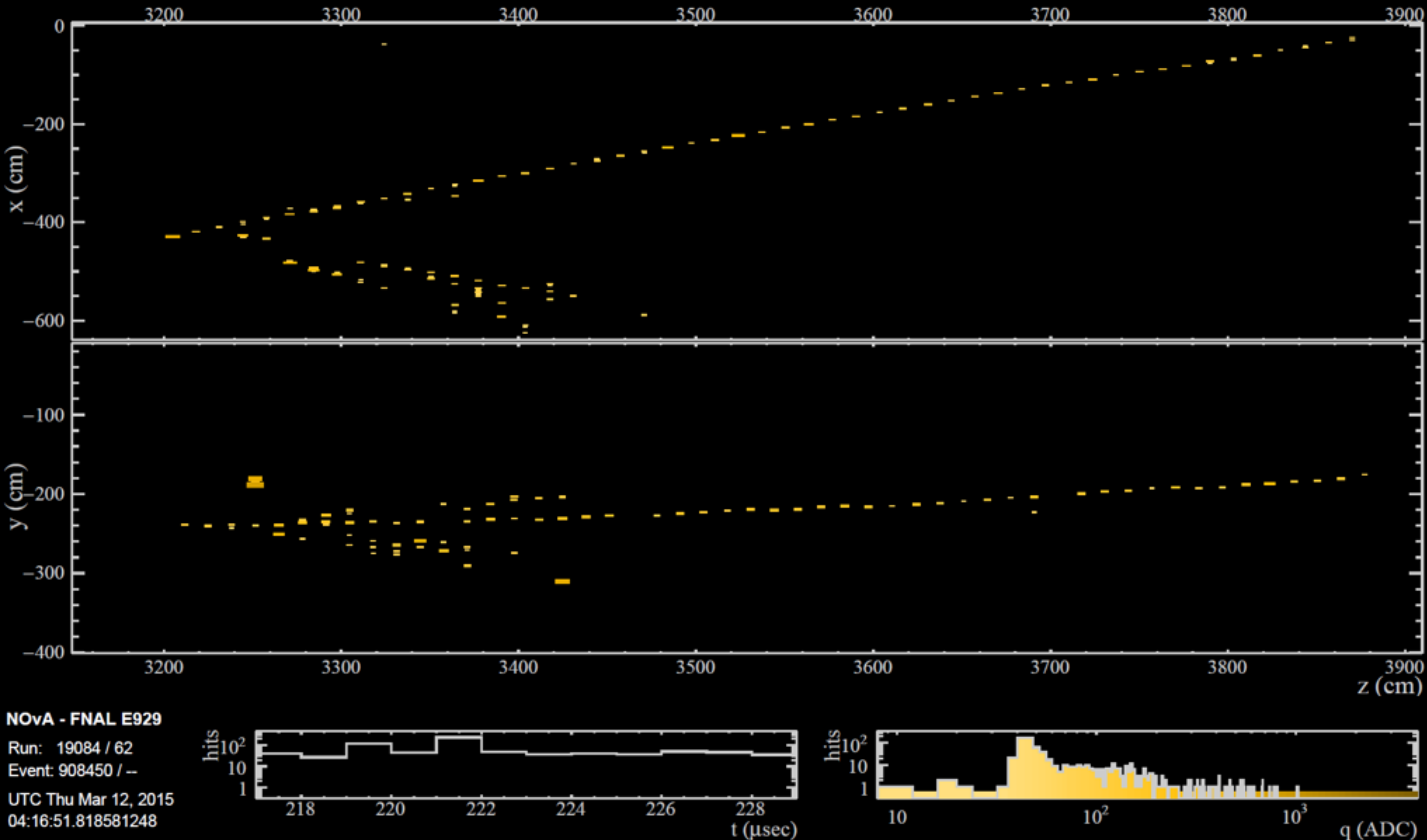
Far Detector selected ν_μ CC candidate



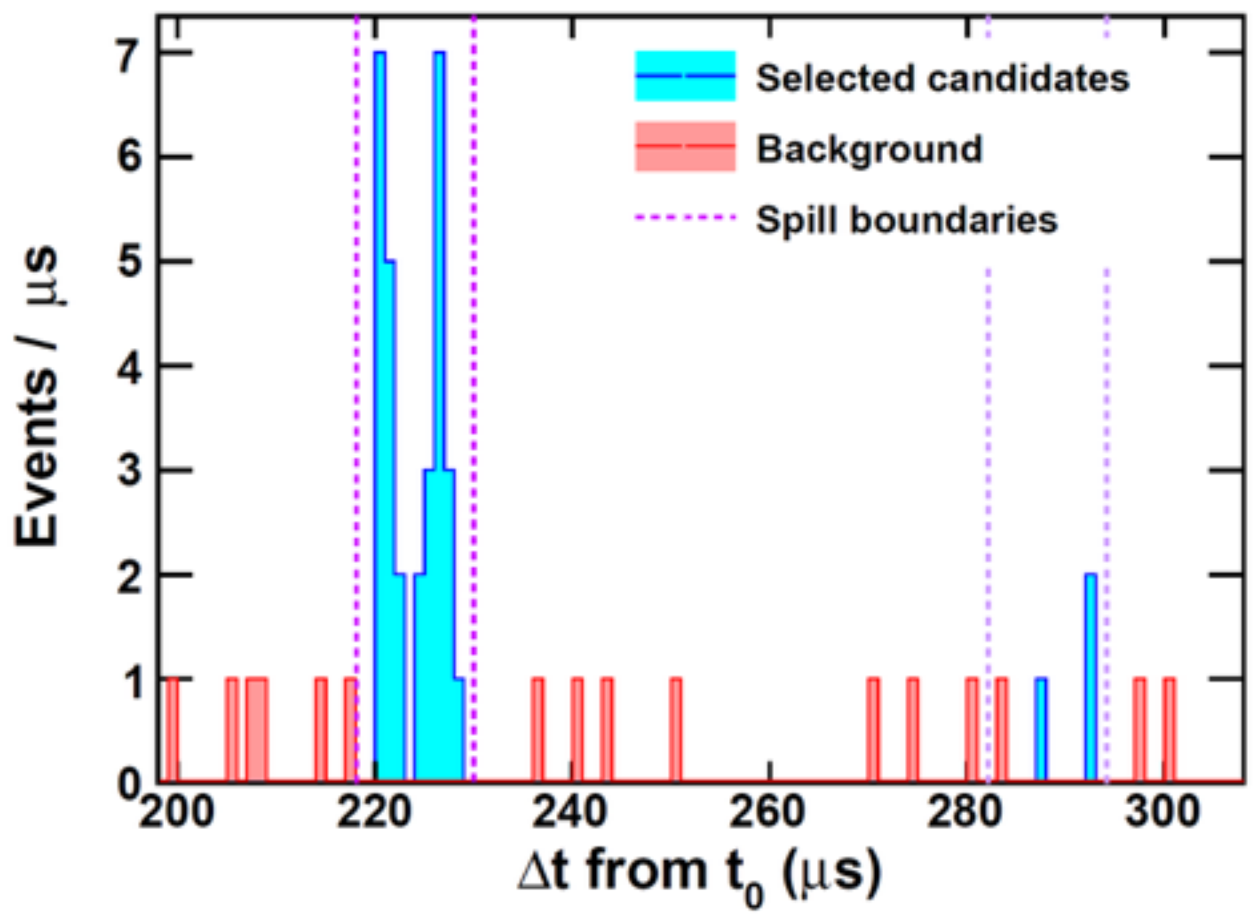
Far Detector selected ν_μ CC candidate

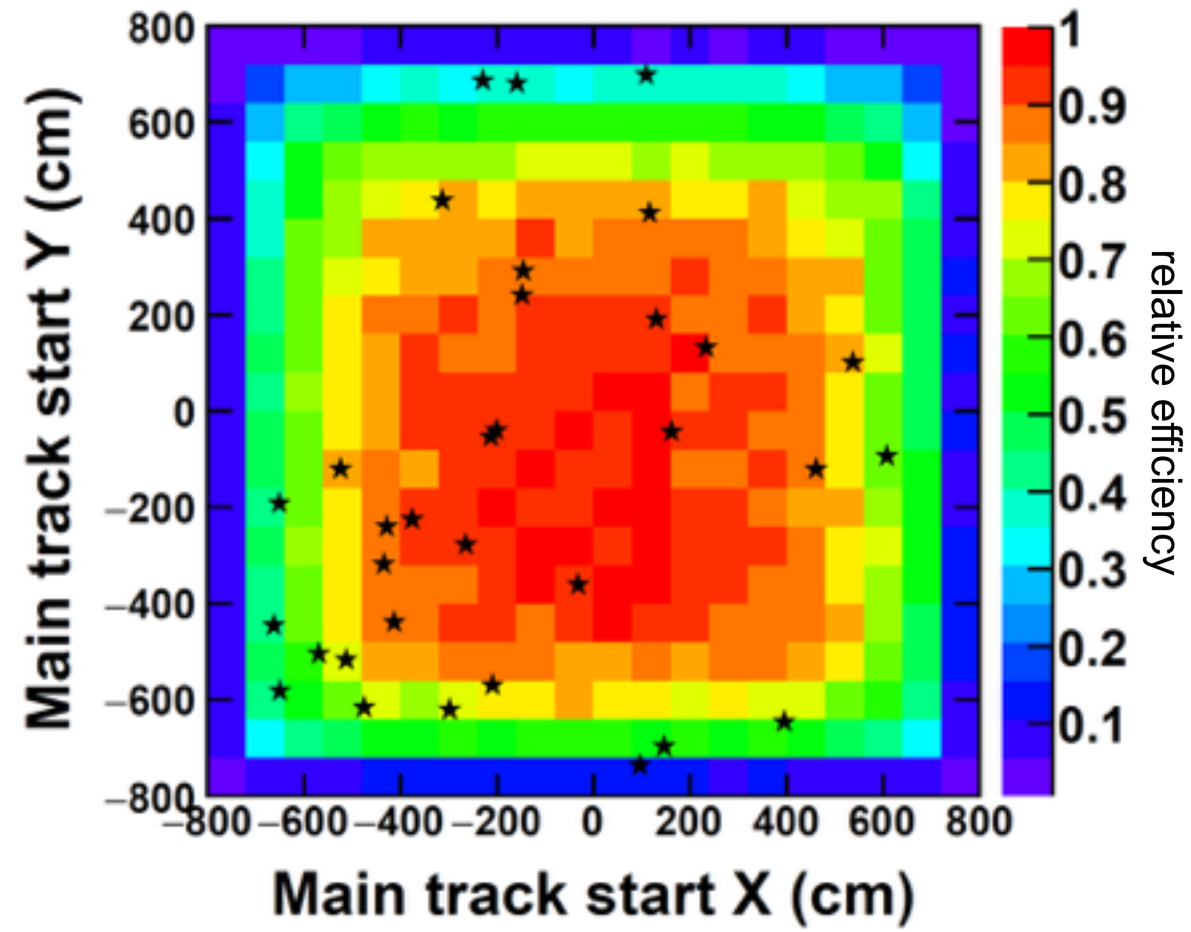


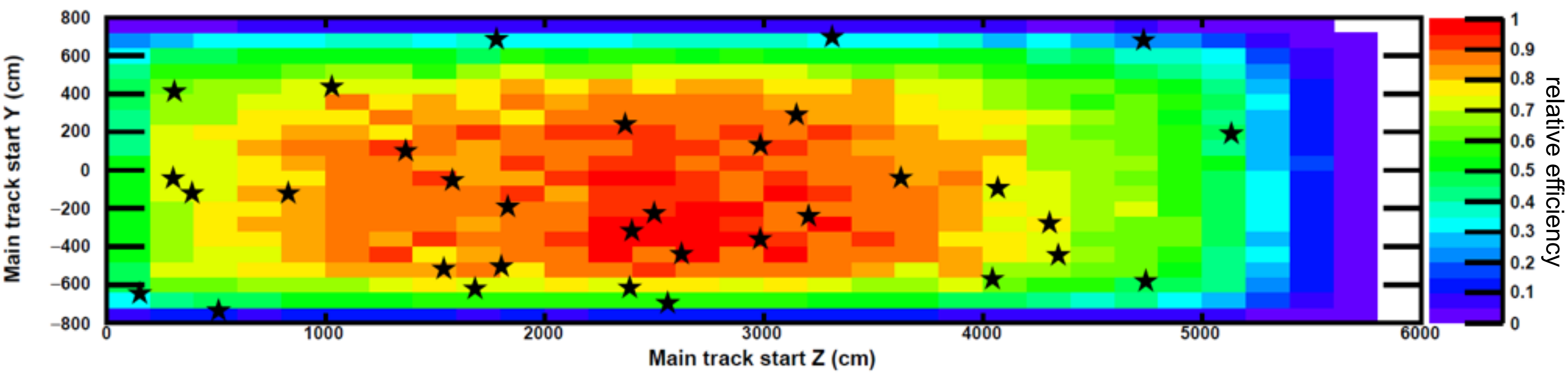
Far Detector selected ν_μ CC candidate



FD ν_μ CC candidates: when and where



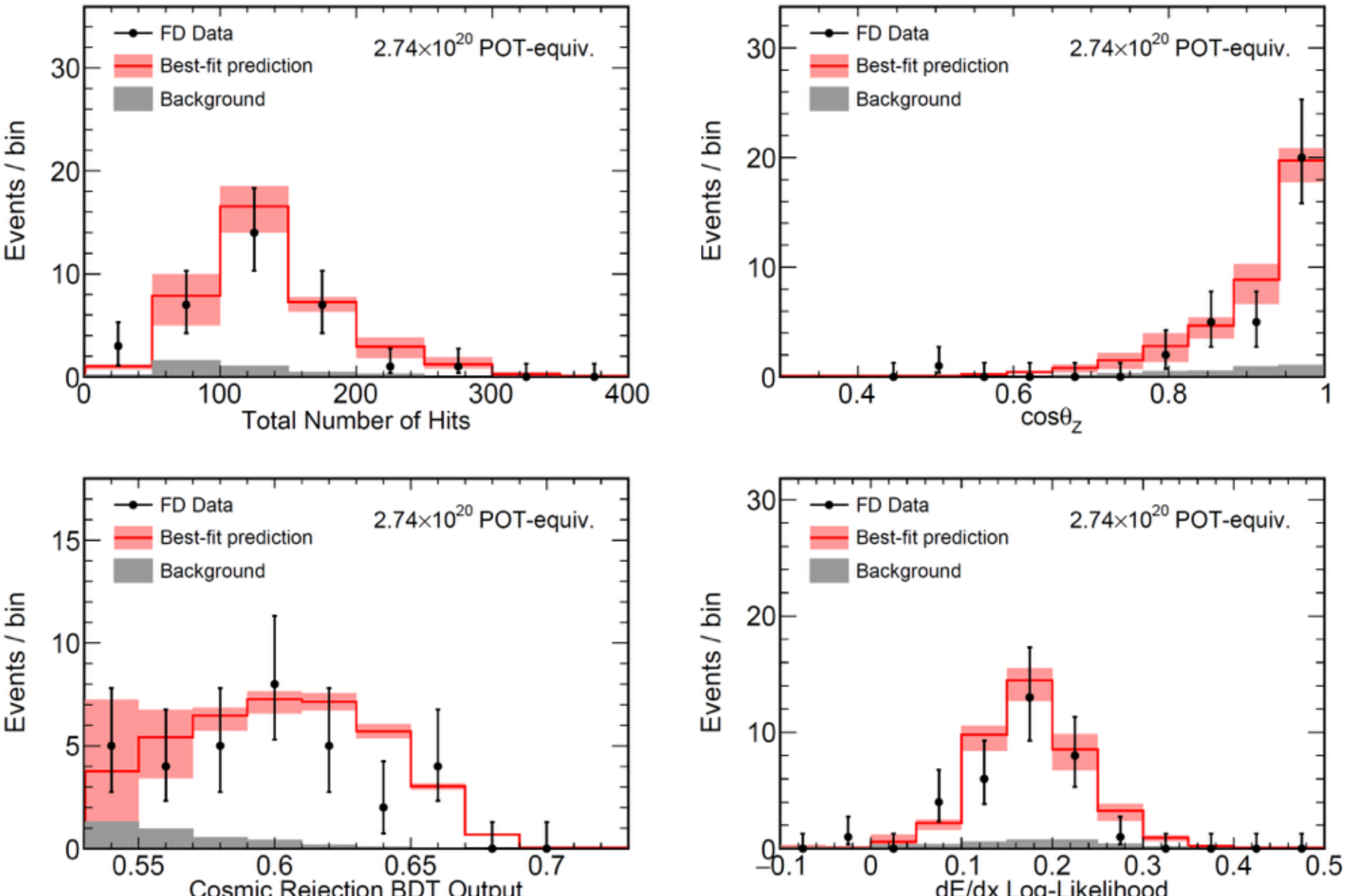




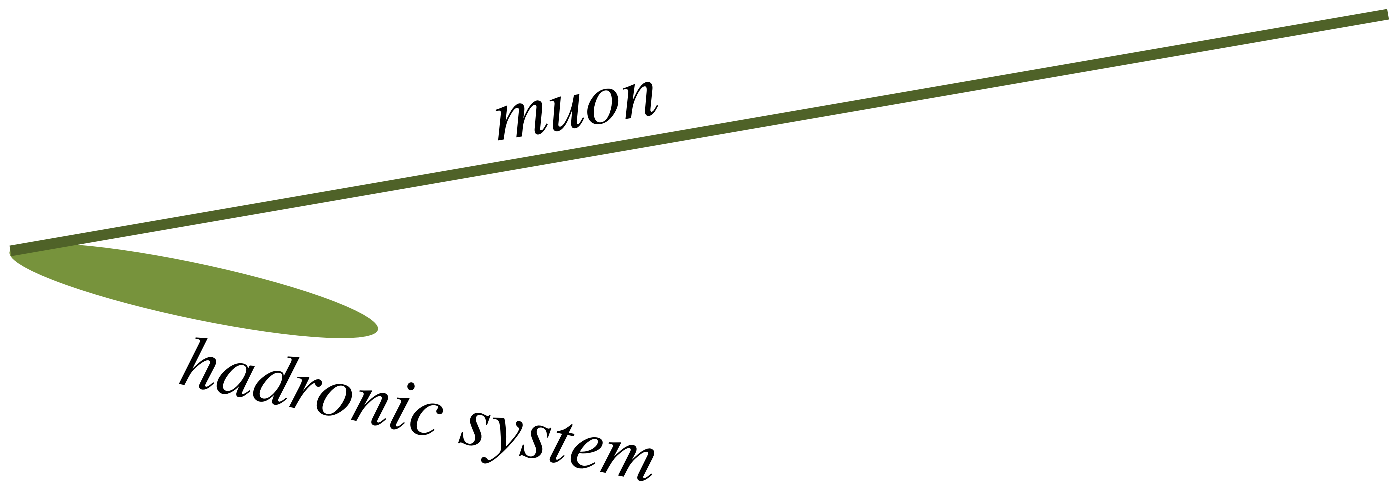
Note 1: Second timing window at +64 musec required for some of the early data
Note 2: Colors show relative efficiency. Not weighted by time variation in detector size.

FD ν_μ CC candidates: event distributions

All NOνA Preliminary



Energy estimation



Reconstructed muon track:

length $\Rightarrow E_\mu$

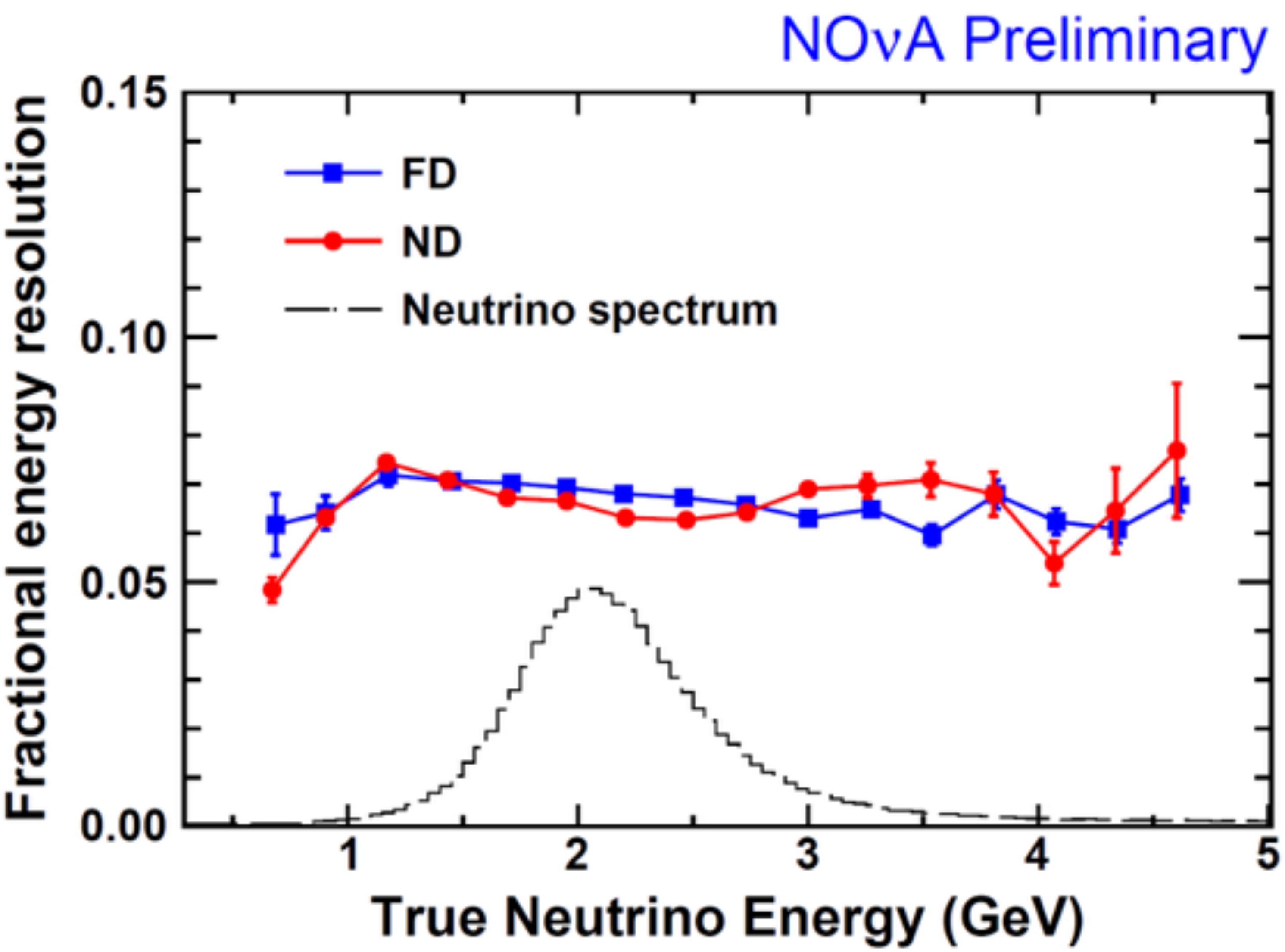
Hadronic system:

$\sum_{\text{cells}} E_{\text{visible}} \Rightarrow E_{\text{had}}$

Reconstructed ν_μ energy is the sum of these two:

$$E_\nu = E_\mu + E_{\text{had}}$$

Energy resolution at beam peak ~7%

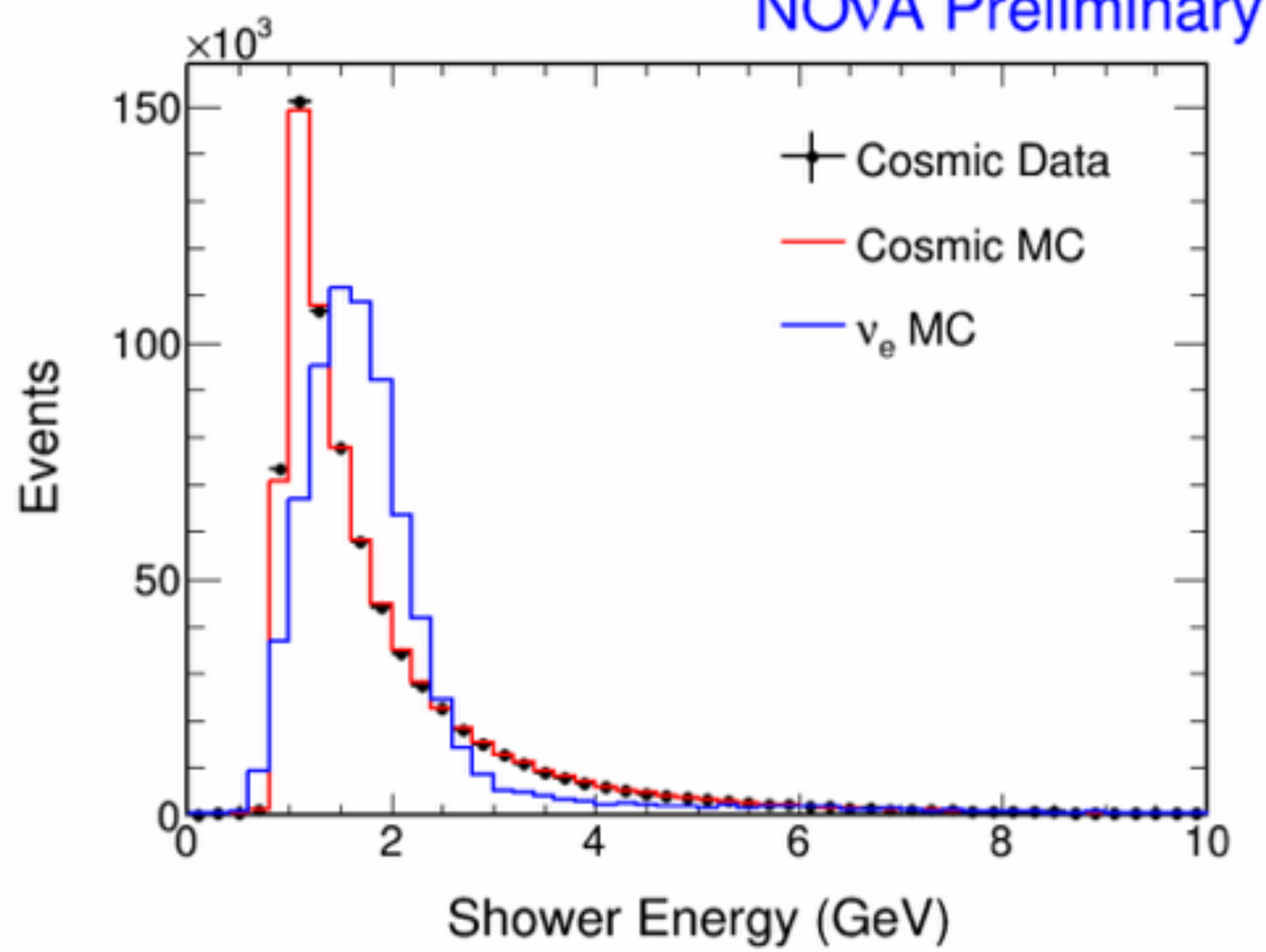


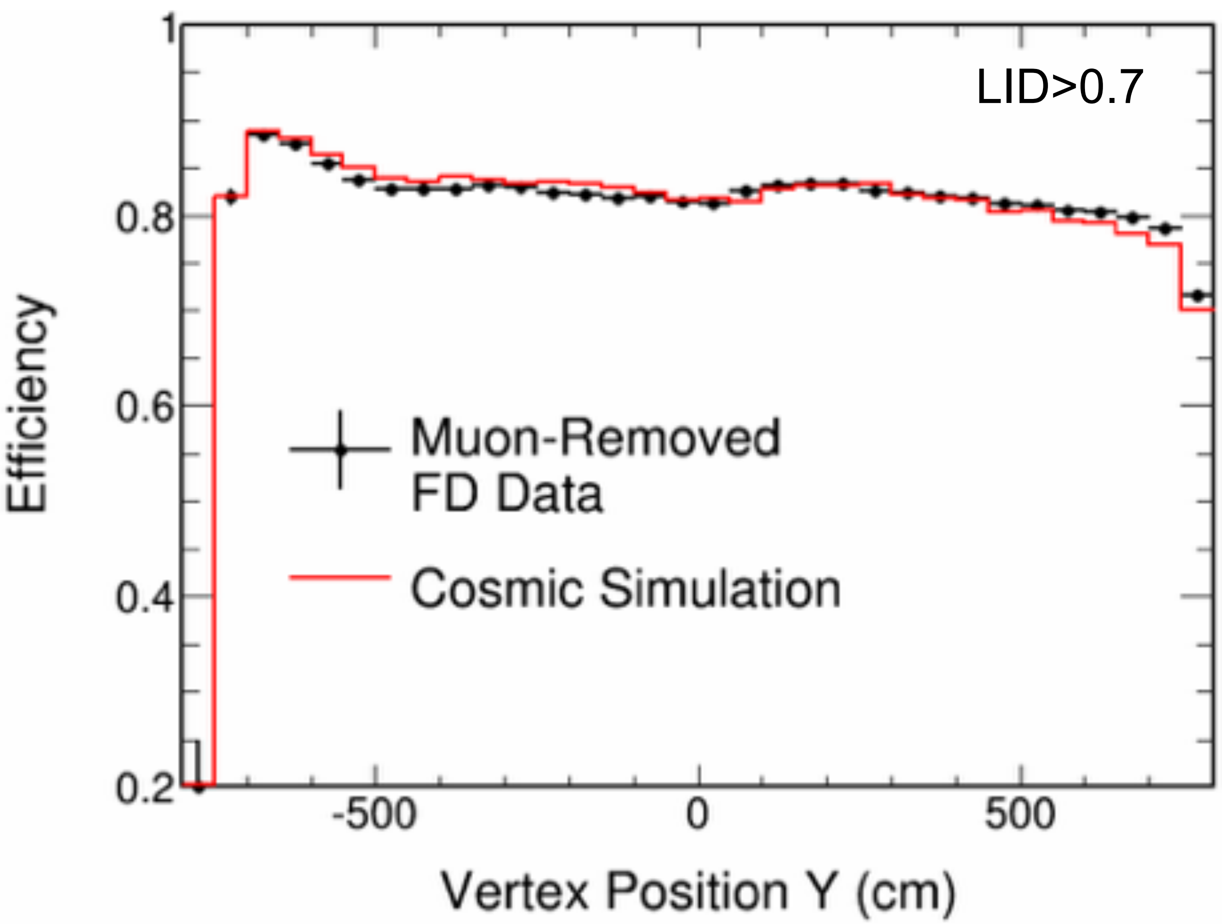
Checks of EM shower modeling

In addition to π^0 in the ND, we have **bremsstrahlung photons in ND and FD**

Right: **energies of brem showers** in FD
- *Excellent data/MC agreement*
- *Probes relevant E range (blue curve)*

Below: **selection efficiency** varies a bit across the large Far Detector
- ***Well modeled by simulation***





ratio →